The Power Output Characteristics of Downhill Mountain Biking

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ABSTRACT

Purpose: To determine the performance characteristics of field-based Downhill Mountain biking (DH) and to identify the best methods of assessment for DH type activity. **Methods:** Twelve trained male cyclists of differing experience levels (age 31.4 ± 9.8 yrs, mean ± s.d.), performed a single laboratory-based intermittent cycle test consisting of 12 all out efforts, separated by periods of passive recovery ranging from 5 to 15 seconds and a continual incremental ramp test to exhaustion. Power output was recorded using a Polar S710 heart rate monitor and power sensor kit and a Schoberer Rad Messetechnik (SRM) Powermeter system during each test. Additionally, seventeen national level trained, male downhill cyclists (age 27.1 ± 5.1 yrs) performed two timed field-based runs of a measured DH course. An SRM Powermeter was used to record power, cadence and speed. Heart rate was again recorded via a Polar S710 monitor. **Results:** During intermittent tests significant differences ($p<0.05$) in power were found at 8 of the 12 efforts. A significant difference ($p<0.001$) was also found when power was averaged over all 12 intervals. Mean power was 556 ± 102 W and 446 ± 61 W for the SRM and S710 respectively. The S710 underestimated power by an average of 23% with random errors of */÷ 24% when compared to the SRM. Random errors ranged from 36% to 141% with the median being 51%. Significant differences ($p<0.001$) were also found between the two systems during the incremental ramp tests. Mean power output was 189 ± 51 W and 212 ± 49 W for the SRM and S710 respectively. The S710 overestimated power by an average of 11 % over the SRM. Random errors ranged from 21% to 67% with the median being 13%. During field-testing peak power was 834 ± 129 W. Mean power (75 W) accounted for only 9% of peak values. Paradoxically, mean heart rate was 168 ± 9 beats.min^{-1}, accounting for 89% of age-predicted maximum heart rate. Mean cadence (28 ± 20 revs.min^{-1}) was significantly related to speed ($r = 0.51$; $p<0.01$). Power and cadence were not significantly related to run time or any other variable. **Conclusions:** Results indicated there was little agreement between the two ergometer systems. The Polar S710 did not provide a valid measure of power during intermittent DH type cycling activity, nor did it provide a valid measure for scientific/elite use during continuous type cycling activity. Errors in the S710 system were potentially influenced by chain vibration and sampling rates. Field results support the intermittent nature of DH Mountain biking. The poor relationships between power and cadence to run time suggest they are not essential pre-requisites to performance in DH and indicate the importance of riding dynamics to overall performance.

Keywords: Downhill, Mountain biking, power output, intermittent activity.

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TERMS AND DEFINITIONS

Aerobic	Refers to activity or processes that require the presence of oxygen.
Anaerobic	Refers to activity or processes that do not require the presence of oxygen.
AT	Anaerobic threshold - the point at which aerobic energy production is supplemented by anaerobic energy production resulting in an increase in lactate acidosis.
Cadence	This is the number of crank arm revolutions every minute and is expressed as $revs.min^{-1}$.
Chain slap	This is when the chain of a bicycle repeatedly slaps against the chainstay of the frame.
Chain slip	Refers to the chain slipping or jumping from cog to cog. This can result in chain derailment when pedalling over rough terrain as encountered during events like Downhill mountain biking.
DH	Downhill mountain biking (DH) is a timed event against the clock and involves riders competing over a measured downhill course.
DOMS	Delayed onset muscle soreness (DOMS) refers to muscle pain and soreness that results for structural disruption of the muscle fibres. It occurs 24 to 48 hours after exercise.
ECG	Electrocardiogram (ECG) is a trace of the hearts electrical activity.
EMG	Electromyography (EMG) is the assessment of a muscles electrical activity.
Ergometer	This is a device for measuring the amount of power produced. Resistance or load can be preset using an ergometer.
LT	Lactate threshold (LT) is the point at which blood lactate begins to accumulate above normal resting levels. LT occurs at ~4 mmol/L of blood.
MVC	Maximal voluntary contraction (MVC) is the maximal contraction force exerted by a muscle and is used as a measure of strength.
Power	Is as function of strength and speed and has been defined as the work done in a unit of time. In sports and exercise power is expressed in watts (W).
Power measuring device	These devices are used to measure and record the power output of a subject. However, unlike ergometers load cannot be preset.
RD	Road cycling (RD) is an endurance event. Unlike XC races, road races are held on tarmac road and can last between 4-7 hours.
RER	Respiratory exchange ratio (RER) is the ratio of carbon dioxide (CO_2) produced to oxygen (O_2) consumed. It is calculated by $CO_2 \div O_2$.
$\dot{V}O_{2max}$	Maximal oxygen uptake, referred to as $\dot{V}O_{2max}$, is the maximum amount of oxygen that can be consumed and used every minute. It is expressed as either litre per minute (absolute) or millilitres per kilogram per minute (relative).
XC	Cross country mountain biking (XC) is an endurance event typically lasting 2-3 hours. Races take place on an off road circuit.

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CHAPTER ONE – INTRODUCTION

Mountain biking has become increasingly popular as both a sport and leisure activity over the past decade (Baron, 2001). The sport encompasses several disciplines with cross-country (XC) and downhill (DH) being two of the most high profile. Both disciplines held their inaugural World Championships in 1990 with cross-country gaining acceptance as an Olympic event in 1996. Though not an Olympic sport, downhill has a similar high profile, and is rapidly becoming one of the most popular of the mountain bike disciplines with its own World cup competition and numerous other global competitions. At a recent World cup event (May, 2004) held at Fort William in Scotland, over 20000 spectators viewed the downhill event, emphasising the sports popularity (Waugh, 2004).

Downhill mountain biking has developed far beyond its origins, when the sports pioneers would modify beach cruiser bicycles and race each other down open fire roads. Today, DH involves trained athletes competing over a measured course against the clock. Competitors usually perform two timed runs, with their fastest run counting towards the final result. The majority of UK DH races are typically between 2 and 4 minutes in duration, and require competitors to ride over a variety of terrain. These range from fast open fire roads, rock strewn paths and technically demanding single-track trails. Courses also include a number of obstacles such as jumps and vertical drops. In many European races riders start high above the cloud line and finish in Alpine valleys where temperatures can be as much as 15°C higher than those at the top of the course, though these are at the upper end in terms of duration at close to 5 minutes. Downhill's governing body, the International Cyclists Union (UCI) states that for DH competitions, events must not exceed 5 minutes and that the emphasis should be on testing the riders' skill and not on pedalling (UCI Regulations, Part IV, Chapter 3, p.9).

Downhill is an intermittent activity, unlike XC riding, which is predominantly continuous in nature. The difference in profiles and the dynamics of each sport have lead to discipline specific developments in terms of both training and equipment. Early mountain bikers would use one race bike for both XC and DH (Metcalfe, 2002). However, as DH courses became more technical and demanding, DH bicycles became more specific. Today's DH bicycles have up to 9 inches of front and rear suspension travel, hydraulic brake systems and only 9 gears, as opposed to 27 on XC bikes, and are too heavy and impractical for use in XC racing. Likewise, modern XC bicycles would not withstand the rigours of a DH course. Today, riders generally opt to compete in only one of the two disciplines, as training is highly specific. Despite such popularity there is a dearth of information assessing the energetics of mountain biking (Atkinson *et al.*, 2003), and in particular the DH discipline.

The aims of the current study were to provide the first reported details of power output characteristics during field-based Downhill riding, and to determine the best method of assessing these characteristics. The best method was determined through the investigation of agreement between two mobile cycle ergometer systems, the Polar S710 and SRM Powermeter, in recording power output during intermittent cycling activity, commensurate with the Downhill discipline. Additionally, agreement between the two ergometer systems during continuous activity was assessed to confirm the validity of the systems under such conditions.

CHAPTER TWO – REVIEW OF LITERATURE

The energetics of Mountain biking

Cross-country mountain bike races typically involve riders competing over varied terrain from woodland trails to forestry roads and include a significant volume of hill climbing, approximately 40 percent of total race distance. This type of racing typically lasts between 2-3 hours (Lee *et al.*, 2002).

Despite the increase in popularity of mountain biking over the past decade there have been relatively few published studies pertaining to the physiological characteristics of mountain biking. Research by Impellizzeri *et al.* (2002) examined the intensity and exercise characteristics of off road cycling. They found that during summer test sessions elite XC cyclists elicited maximal oxygen uptake ($\dot{V}O_{2max}$) values of 4.88 ± 0.4 $L.min^{-1}$. These results were comparable to those obtained by Baron (2001). However, when $\dot{V}O_{2max}$ was expressed relative to body mass the cyclists studied by Impellizzeri *et al.* (2002) demonstrated higher values to those studied by Baron (2001) (75.9 ± 5.0 and 68.4 ± 3.8 $mL.kg^{-1}.min^{-1}$ respectively). This would suggest that the elite cyclists tested by Impellizzeri *et al.* (2002) were of a higher competitive level than those in the Baron (2001) study.

The $\dot{V}O_{2max}$ values described above are comparable to those of professional and elite road cyclists (RD) cyclists. Lucía *et al.* (2001) showed that when expressed relatively to body mass RD cyclists elicited $\dot{V}O_{2max}$ values of 70 to 80 $mL.kg^{-1}.min^{-1}$. This would suggest that a high level of aerobic fitness is important to success in both the XC and RD racing disciplines.

Despite the similarities in $\dot{V}O_{2max}$ between RD and XC cyclists, the findings do not explain the performance differences between elite level amateur cyclists and professional cyclists. This highlights the poor reliability of using $\dot{V}O_{2max}$ as a predictor of exercise performance. Lucía *et al.* (1998) proposed that the differences between these two groups might be due to improved fat metabolism at submaximal and high intensity levels in professional cyclists and a better tolerance to lactate accumulation. They also suggested that when predicting performance, it would be better to analyse the percentage of $\dot{V}O_{2max}$ a cyclist could sustain over a period of time. A further possible indicator of performance is the $\dot{V}O_2$ value coinciding with an individuals anaerobic threshold (AT), that being the point at which aerobic energy provision is supplemented by anaerobic provision resulting in a sustained increase in lactate acidosis (Wasserman, 1986).

Padilla *et al.* (1999) looked at different RD groups and found that $\dot{V}O_{2max}$ was significantly higher in flat terrain (FT) and time trial (TT) specialists than in uphill (UH) specialists when expressed in absolute terms (5.67 ± 0.44, 5.65 ± 0.53 and 5.05 ± 0.39 $L.min^{-1}$ respectively). However, when expressed relative to body mass $\dot{V}O_{2max}$ values for the UH cyclists were higher than those of the TT and FT cyclists (80.9 ± 3.9, 79.2 ± 1.1 and 74.4 ± 3.0 $mL.kg^{-1}.min^{-1}$ respectively) indicating a superior power to weight ratio. The XC cyclists studied by Impellizzeri *et al.* (2002) had $\dot{V}O_{2max}$ values comparable to the FT cyclists studied by Padilla *et al.* (1999) despite very similar morphological profiles to the UH cyclists. These differences may be the result of different test protocols or the timing of the tests, as given the volume of climbing involved in XC races and the morphological similarities it is fair to suggest that the $\dot{V}O_{2max}$ characteristics of XC and UH specialists would be comparable.

Impellizzeri *et al.* (2002) showed that the average heart rate (HR) during XC racing was 171 ± 6 $beats.min^{-1}$, equating to 90 percent of maximum heart rate. This is supported by Lee *et al.* (2002), who reported mean percent peak heart rate as 93 ± 2 percent during XC. More recently Stapelfeldt *et al.* (2004) found almost identical results to Impellizzeri *et al.* (2002) during XC testing. Lee *et al.* (2002) also reported percent peak heart rate of 92 ± 3 percent for RD cyclists. This again indicates the similarities between XC and RD riding in terms of physiological demands.

The power output and the physiological profiles of elite level male and female RD and XC cyclists were examined using a progressive protocol to exhaustion (Wilber *et al.*, 1997). They found absolute power was significantly greater (18%) in male RD cyclists than their off-road counterparts. This was also true for relative power ($W.kg^{-1}$) (16% higher) at lactate threshold (LT), that being the point at which blood lactate begins to accumulate above normal resting levels. All other responses between the male athletes in the study were comparable. No significant differences in power were recorded between the female RD and XC athletes. However, contrary to other studies, both absolute and relative $\dot{V}O_{2max}$ values were significantly greater ($p < 0.05$) in the elite female RD cyclists, as was maximal heart rate than in female XC cyclists. This might be due to the higher training mileage covered by the RD cyclists in their study. Maximal exercise responses from the study can be seen in table 1.

	Female		Male	
	XC	RD	XC	RD
$\dot{V}O_{2max}$ ($L.min^{-1}$)	3.33^a ± 0.27	3.85 ± 0.30	4.99 ± 0.44	5.09 ± 0.43
$\dot{V}O_{2max}$ ($mL.kg^{-1}.min^{-1}$)	57.9^a ± 2.8	63.8 ± 4.2	70.0 ± 3.7	70.3 ± 3.2
Lactate ($mmoL.min^{-1}$)	8.7 ± 2.2	10.2 ± 2.5	10.4 ± 2.7	11.8 ± 1.7
Heart Rate (bpm^{-1})	178^a ± 7	188 ± 11	192 ± 12	200 ± 11
Power (W)	313 ± 24	333 ± 21	420^b ± 42	470 ± 35
Power ($W.kg^{-1}$)	5.4 ± 0.4	5.5 ± 0.5	5.9^b ± 0.3	6.5 ± 0.3

[a] significantly different compared to Female road racers.
[b] significantly different compared to Male road racers.
Values are mean ± s.d.

Table 1. Maximal Responses to Cycle Ergometry. Adapted from Wilber *et al.* (1997).

Almost identical results to those of Wilber *et al.* (1997) for values of $\dot{V}O_{2max}$, lactate and power output when expressed in absolute terms have been reported for XC cyclists in subsequent studies (Lee *et al.*, 2002). However, when expressed relative to body mass, power output and $\dot{V}O_{2peak}$ was significantly greater than the off-road cyclists studied by Wilber *et al.* (1997) (Lee *et al.*, 2002). This again could suggest that the athletes tested in the later study had greater power to weight ratios and may have been of a higher competitive level than those tested by Wilber *et al.* (1997).

In the only reported study pertaining to DH, Hurst and Atkins (2002) reported that heart rates were consistently in excess of 176 beats.min^{-1}. However, the results did not highlight the intermittent nature of the activity and inferred a more continuous mode of exercise. Their study proposed that the consistently elevated heart rates might have been a result of additional isometric muscle contractions during non-pedalling phases to aid dampening of trial shocks.

Despite the potential influence of isometric contractions other factors such as hormone activity may also have contributed to the elevated heart rates observed by Hurst and Atkins (2002). Adrenergic stimulation and the release of the catecholamine epinephrine is one of the first responses to exercise and stimulates an increase in HR (Åstrand *et al.*, 2003). During stressful events the body experiences a 'fight or flight' response. Additionally, Kurtis and O'Keefe Jr. (2002) reported that some of the exhilarations of life, otherwise known as adrenaline rushes were also responsible for this fight or flight response. Many extreme sports participants, including DH cyclists, take part in such sports to seek such an adrenaline rush. This response leads to an increase in the release of epinephrine and therefore HR. Downhill cyclists are potentially in a state of fight or flight in order to prepare themselves for sudden unexpected events during the race, such as loss of bicycle control, forced changes to race plans or the threat of accidents, therefore it could be these hormonal changes that contribute to the high elevated HR in DH. However, investigation of these hormone levels would be required to confirm this. No other studies have looked at the characteristics of DH riding.

Mean HR values reported by Hurst and Atkins (2002) were higher than those reported in other studies (Impellizzeri *et al.*, 2002; Stapelfeldt *et al.*, 2004). Values were however comparable to those of professional road cyclists during field-based short duration 'prologue' time trials (177 ± 5 beats.min^{-1}) and equated to 89 ± 3% of HR_{max} (Padilla *et al.*, 2000). Hurst and Atkins (2002) also emphasised a paradox for the assessment of DH performance. Whilst heart rates were remarkably stable throughout the performance, the actual observed pattern of activity was intermittent. This would advocate the use of alternative assessments of energy expenditure to accommodate this intermittent pattern.

Methods of assessing exercise intensity

Introduction to heart rate monitoring

Heart rate monitoring has long been seen as a valid method of determining exercise intensity, this is due to the linear relationship between HR and $\dot{V}O_2$ uptake. Over the past 30 years HR monitoring has been one of the most commonly used methods of monitoring during exercise, particularly out in the field (Terbizan *et al.*, 2002). Polar (Kempele, Finland) introduced the first wireless heart rate monitor, the PE 2000, in 1983. The PE 2000 used electric field data transfer. One year later they introduce the PE 2000's successor, the PE 3000. This was the first heart rate monitor to use magnetic field data transfer. Nowadays most monitors use this method of data transfer (Laukkanen and Vartinen, 1998).

Since the early 1980's heart rate monitors have become increasingly more sophisticated and introduced more and more features. One of the newest monitors is the Polar S710 that is utilised in the present study. The S710 boasts an array of features including heart rate limits, interval training capabilities, OwnCal® calorie counter, power output and numerous functions usually found on a cycling computer. In addition to the array of functions, many modern heart rate monitors now allow the user to download data from training sessions to a personal computer using Windows® based software for easier analysis.

Accuracy of heart rate monitoring

Karvonen *et al.* (1984) examined the validity and accuracy of the PE 2000. They compared this with the Holter electrocardiogram (ECG) monitor and found that heart rates differed by at most 5 beats.min^{-1} over a range of intensities. The accuracy of wireless heart rate monitors has been well documented over the years (Treiber *et al.*, 1989). They looked at the heart rate monitoring of children in a laboratory and out in the field. Their study reported correlation coefficients of >0.93 and standard error of estimation (SEE) of 1.1 to 4.3 beats.min^{-1} between the PE 3000 and ECG derived heart rates.

Further studies have also tested the PE 3000 against ECG apparatus and showed a correlation coefficient of 0.99 over a range of 55-177 beats.min^{-1} (Seaward *et al.*, 1990). These results were almost perfectly replicated in a later study when heart rate was averaged over 10 seconds (Wajciechowski *et al.*, 1991).

Limitations of heart rate monitoring

Despite its popularity there are limitations with monitoring HR as a guide to exercise intensity. Stannard and Thompson (1998) investigated HR as an indicator of exercise intensity under different environmental conditions. A group of highly trained cyclists cycled for 50 mins at powers of 150, 250, 350, 250 and 150 W at temperatures of 37° and 20° Celsius. Heart rate at stage four was on average 26 beats.min^{-1} higher in the hotter condition. Additionally, HR in the hotter condition was on average 18 beats.min^{-1} higher during the 150 W workload at the end of the test than the same workload at the beginning of the test. However, under cooler conditions HR during these workloads was comparable. These results indicate that an athlete exercising in hot climates could underestimate exercise intensity when using HR as an indicator.

This increase in HR is the result of cardiac drift. Cardiac drift occurs due to a variety of factors such as physical conditioning, health, rate of fatigue, hydration and body heat regulation. As we exercise in hot weather there is an increase in the sweat response and subsequently blood plasma volume decreases as fluid moves out of the blood and into the surrounding cells and tissue. Additionally, during exercise blood is shunted away from non-vital organs to working muscles and also to the skin to aid heat loss. This results in a reduction in venous blood returning to the heart and a decrease in stroke volume. To compensate for these responses HR increases. During short repeated intervals this can be between 3 and 5 beats.min^{-1}, but in exercise over 30 mins it can be as much as 20 beats.min^{-1} (Foss and Keteyian, 1998).

Isometric muscular activity can also affect heart rates. Smolander *et al.* (1998) investigated the effects of isometric contractions during a handgrip test and knee extension at 20, 40 and 60 percent of maximal voluntary contraction (MVC). They found that HR increased in relation to isometric contraction time and that the quadriceps muscles (knee extension) fatigued more quickly then finger flexor muscles (handgrip). As DH involves the isometric contraction of both these muscle groups, such isometric activity may have also contributed to the consistently elevated HR's observed by Hurst and Atkins (2002).

Gnehm *et al.* (1997) also reported that body position can affect HR. They found that HR was on average 5 beats.min^{-1} higher in the aerodynamic position than in an upright position and on the 'drops' of a road bicycles handlebars. This may also have been the result of increased isometric contractions of the upper body to hold the aerodynamic position.

During DH mountain biking, position on the bike is constantly changing in order to manoeuvre the bicycle over obstacles on the course. During longer fire road sections the rider will often adopt an aerodynamic crouched position on the bike, whilst on approach to obstacles the rider will generally stand tall on the pedals. Contrary to the findings of Gnehm *et al.* (1997) these changes in body position would potentially have little effect on HR in DH as this has been shown to be elevated already by Hurst and Atkins (2002). Additionally, changes in HR response time to changes in body position and exercise intensity would be much slower than the actual changes in body position, therefore would most likely not be highlighted from heart rate monitoring. Jeukendrup and Van Diemen (1998) reported that this lag time could be up to 30 s and take between 2-3 mins to completely adjust to the changes in intensity.

Despite the high reliability of Polar monitors reported by researchers, the use of heart rate monitoring in DH to assess exercise intensity is questionable. Heart rate responses were monitored for DH and XC cyclists over a measured downhill course (Hurst and Atkins, 2002). Their results found mean HR was 176 ± 13 beats.min^{-1} and 172 ± 14 beats.min^{-1} for the DH and XC cyclists respectively. These results indicated the subjects were performing at a high intensity and suggest that they were performing at an almost constant workload throughout the trials. This can be seen in figure 1. However, downhill is intermittent in nature with frequent periods of non-pedalling. Heart rates from the Hurst and Atkins (2002) study do not reflect the intermittent nature of the activity. This emphasises the influence that exercise mode can have on HR. This makes HR monitoring inappropriate as a method of testing during this type of activity and Hurst and Atkins (2002) proposed that power output assessment would have given a more accurate indication of how hard the subjects were working.

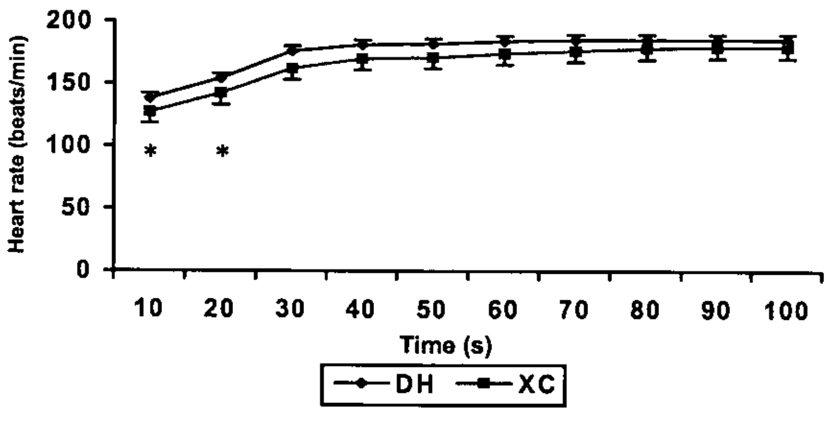

Figure 1. Mean heart rate response to downhill riding. (*) indicates significant differences (p<0.05). Data averaged for each 10 s interval.

Regardless of the limitations of heart rate monitoring, it still remains one of the most commonly used methods of assessing fitness and exercise intensity. This is in part due to the low cost of heart rate monitors and their ease of use. These two factors have made this method particularly appealing to recreational athletes and fitness enthusiasts. However, as a result of more recent research, more sports scientists and coaches are now starting to use power output assessments as a more direct measurement of exercise intensity than HR monitoring.

Maximal oxygen uptake is another popular method of assessing energy expenditure and has been widely accepted as the best measure of cardiovascular functionality and a high $\dot{V}O_{2max}$ has often been used as a good indicator of athletic performance. However, over the past 70 years this concept has been regularly challenged (Bassett and Howley, 2000). As downhill events rarely exceed 4 minutes in duration, a high $\dot{V}O_{2max}$ would not necessarily identify better performers over athletes with lower $\dot{V}O_{2max}$ values in this type of event. Subsequently, other methods of assessing energy expenditure during DH type activity would need to be employed, such as assessments of power output.

Application of assessment methods to Downhill Mountain biking

Though heart rate monitoring and the assessment of oxygen uptake are both valid means of determining energy expenditure in both a laboratory and field setting, there are constraints that limit their use for determining the energetics of Downhill Mountain biking. As previously discussed, heart rate monitoring does not detect the intermittent nature of DH and would infer a more continuous exercise intensity. Likewise, the assessment of $\dot{V}O_2$ during field-based DH is problematic. The assessment of $\dot{V}O_2$ during continuous type cycling in the field is possible with few problems using systems such as the Cosmed K4 b2 portable gas analyser. This system has been validated by Hausswirth *et al.* (1997). However, the Cosmed system is relatively bulky and would hinder the movement of the rider during DH. This is less of a problem with XC and RD cycling, as in both disciplines, particularly road cycling, body position remains relatively still on the bike. Another issue with using the Cosmed during DH is safety. Should a cyclist fall off, as is a frequent occurrence in DH, they may land on the portable unit causing injury to the chest area and irreparable damage to the apparatus.

Downhill mountain biking is unlike any other cycling discipline in terms of riding characteristics and is likely to produce completely different physiological parameters to XC and RD riding. As a result of the issues associated with heart rate monitoring and $\dot{V}O_2$ assessment during field-based DH riding, power output would again appear to be a more valid means of assessing the energy dynamics of this discipline.

Power output and performance

Introduction to power output

Power has been defined as the work done in a unit of time or the rate of performing work and is expressed in watts (W) (Foss and Keteyian, 1998). Power output, both aerobic and anaerobic is a crucial element of fitness for competitive cyclists of all disciplines and is now widely acknowledged as a more direct measurement of exercise intensity than heart rate monitoring (Jeukendrup and Van-Diemen, 1998). However, despite the plethora of research into the power output of road cycling (Lucía *et al.*, 1998; Padilla *et al.*, 1999 and 2000) there has been very little research into the power output of mountain biking, particularly the DH discipline. The vast majority of studies into cycling and power have examined aerobic power output and have employed continuous protocols to do so. Significantly fewer studies have looked at high intensity intermittent power output such as is needed for DH cycling.

Different studies will refer to the highest obtained power output as either maximal or peak power, as can be seen in the following review of literature. However, to use to term maximal power is somewhat misleading. This would imply that the power value obtained was the highest the athlete had ever elicited and could elicit. Conversely, peak power refers to the highest value obtained on a particular occasion. Consequently all results in the present study more accurately refer to peak values.

Power output and cadence

Morton (1990) looked at modelling human power and endurance. He reported that the time course of maximal power during exercise was dependent upon both physiological and neuromuscular fatigue and that the major contributing factor to fatigue was a reduction in the contractile efficiency of the muscle. Morton (1990) found that maximal exertable power declined rapidly after approximately 6 s at 972 W. This can be seen in figure 2. Morton also reported that between powers of 208 W and 972 W endurance declined from ad infinitum to 6 s.

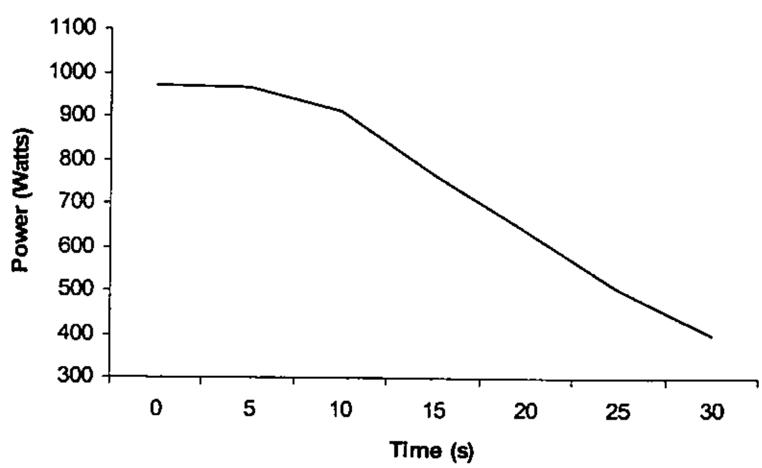

Figure 2. Power-Duration Relationship. Redrawn from Morton (1990).

Over the past few decades sports scientists and coaches have studied the power-duration relationship and its influencing factors in depth in order to determine the optimal power output and cadence that would elicit maximal performance in various cycling disciplines. No published studies have looked at these variables with respect to the DH discipline.

Research on the force-velocity relationship found that peak torque, as tested on an isokinetic dynamometer, decreased with increasing speed of muscle shortening (Thorstensson *et al.*, 1976). Their findings further supported the earlier work of Moffroid *et al.* (1969). As DH potentially involves high cadence bursts of effort, and therefore rapid muscular contractions, the force-velocity relationship might be influential in the generation of power during this type of activity.

The forces and power produced during short-term dynamic exercise on a cycle ergometer was examined by using a modified cycle ergometer fitted with a 3 horsepower (hp) electric motor that would turn the cranks at a pre-selected speed between 23 and 171 revs.min^{-1} (Sargeant *et al.*, 1981). The cranks then had a series of strain gauges bonded to them to measure power output. This modification converted the cranks into what was essentially an early version of today's SRM Powermeter used in the present study and made the ergometer into an isokinetic ergometer, controlling the speed of muscular contractions.

Subjects were asked to perform a series of 20-second maximal effort bursts on the ergometer. The results of the tests showed peak force measured in kilograms of force (Kgf) reached maximum levels during the first few revolutions, thereafter peak force decreased with increasing crank velocity. These results are what would be expected from a Wingate type anaerobic test, where force measured as peak power (W_{peak}) would be maximal during the initial few seconds of the test with a rapid decrease in power over the remainder of the exercise period due to muscular fatigue (McArdle *et al.*, 1996).

Sargeant *et al.* (1981) also found that the optimal cadence for producing the greatest mean power (665 ± 113 W) and W_{peak} (840 ± 153 W) was approximately 110 revs.min^{-1}. Above this cadence power output decreased. Like the tests conducted by Sargeant *et al.* (1981) DH is short-term and dynamic in nature, with events lasting approximately 3 minutes. During DH events competitors rarely pedal for more than 10 to 15 seconds at any time; therefore the cadences suggested by Sargeant *et al.* (1981) would appear to be applicable to DH cycling for the development of maximal power. However, visual observations suggest that the pedalling dynamics of DH cyclists vary considerably with some riders appearing to pedal at cadences greater than 110 revs.min^{-1} while other riders pedal at much lower cadences, yet riders can post comparable run times irrespective of cadence preference. This may be the result of specific 'spinning' and 'overspeed' training employed by some DH cyclists and the technical abilities of others. Overspeed training has been shown to help increase power and speed through training the muscles to work at a higher rate than normally encountered during competition thereby improving neuromuscular activity and recruitment of motor units (Hammett and Hey, 2003). However, the study by Hammett and Hey (2003) was conducted with high school track athletes and despite high profile cyclists and coaches such as Lance Armstrong and Chris Carmichael (2003) advocating the benefits of overspeed training for cyclists, scientific evidence to support this remains scarce.

There have been several studies that have looked at the pedalling economy of cyclists (Seabury *et al.*, 1977; Coast and Welch, 1985). Many of these studies recommend a cadence of between 40–70 revs.min^{-1} as being the most economical and that this cadence increases with increasing power output. Research into total pedalling force as a function of pedalling rate and power output by Patterson and Moreno (1990) suggested a higher optimal pedalling rate of between 90-100 revs.min^{-1}.

Baron (2001) found that between cadences of 50-140 revs.min^{-1} W_{peak} corresponded to an optimal pedalling cadence of approximately 100 revs.min^{-1} in both XC cyclists and sports students. Patterson and Moreno (1990) found that these higher cadences also helped to reduce peripheral muscular fatigue despite an increase in oxygen uptake. Takaishi *et al.* (1996) support these findings as their research showed that well trained cyclists prefer to pedal at higher cadences in order to help minimise fatigue.

Higher cadences may have a beneficial effect on muscular fatigue during endurance cycling such as RD cycling and XC mountain biking. However, DH cycling utilises much lower gear ratios than those used in RD and XC during maximal efforts, therefore the use of higher cadences would possibly be of minimal benefit as muscular tension may be much lower than in other cycling disciplines following an initial maximal effort. Additionally, in DH cycling the positive effects of a high cadence will potentially be cancelled out by the eccentric action of the working muscles in order to absorb the large shocks and bumps of the course. Skurvydas (2000) demonstrated a significant decrease in muscular contraction force following intermittent eccentric exercise. Eccentric exercise leads to rapid fatigue and is a contributing factor in delayed onset muscle soreness (DOMS), as it results in structural disruption of the muscle fibres (Brooks *et al.*, 2005). Though higher cadences may reduce peripheral fatigue as proposed by Patterson and Moreno (1990) they cannot counteract the large drops and bumps of a DH course that require the muscles to contract eccentrically to dampen them, therefore cadence is likely to have little effect on reducing muscular fatigue in DH riding.

MacIntosh *et al.* (2000) studied how cadence and power affected muscle activation. Subjects were asked to perform a series of randomised maximal efforts at different cadence-resistance combinations. They discovered that as workload increased the cadence that was required to initiate minimal muscle activation (lowest amplitude EMG) also increased. It was also found that peak power occurred at progressively higher cadences as power increased, as shown in figure 3. At a power output of 400 W it was established that optimal cadence was approximately 100 revs.min^{-1}. These results further advocate the use of high pedalling rates for optimal performance.

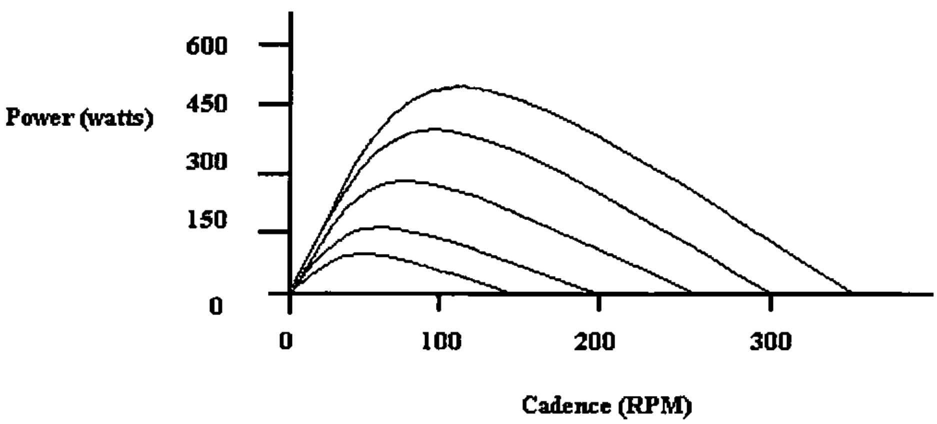

Figure 3. Schematic representation of responses to differing power/cadence combinations. Redrawn from MacIntosh *et al.* (2000).

Unlike the high cadences recommended by Patterson and Moreno (1990) and Sargeant *et al.* (1981) for generating W_{peak}, when it came to prolonged periods of cycling, Hill *et al.* (1995) found critical power, that is the theoretical power output that can be sustained indefinitely before the onset of fatigue, was lower at high cadences than at low cadences. They reported values of 194 ± 50 W at 100 $revs.min^{-1}$, 204 ± 48 W at varying $revs.min^{-1}$, and 207 ± 50 W at 60 $revs.min^{-1}$.

McNaughton and Thomas (1996) further support the use of lower pedalling cadences. They looked at the effect different pedalling cadences had on the power-duration relationship in recreational cyclists. McNaughton and Thomas (1996) hypothesised that endurance performance would be impaired at higher pedalling rates. They demonstrated that at 50 $revs.min^{-1}$ recreational cyclists performed 16 percent longer than at 110 $revs.min^{-1}$ and 9 percent longer than at 90 $revs.min^{-1}$ with no difference in power output. A similar study previously conducted by Carnevale and Gaesser (1991) found comparable results.

High power outputs and high cadences would potentially be observed during the simulated DH protocol within the laboratory environment in the present study, as downhilling involves high intensity bursts often performed at cadences well above 100 $revs.min^{-1}$. This may also be the case during the field-based tests, though course profile and riding styles might affect the riding characteristics.

Aerobic fitness and power output

Another research area pertaining to power output has been the effect of aerobic fitness. Research by McMahon and Wenger (1998) looked at the relationship between aerobic fitness and power output and its role in recovery during maximal intermittent exercise. They found that both mean and peak power decreased significantly, 26 percent and 25 percent respectively, from an initial 15-second bout of maximal exercise to the sixth bout.

McMahon and Wenger (1998) also demonstrated that athletes with an elevated $\dot{V}O_{2max}$ during the active recovery phase were more efficient in returning the active muscles to their pre-exercise homeostatic state, potentially due to a more efficient return of pH towards resting levels. According to McMahon and Wenger (1998) this may lead to a reduce inhibition of the creatine phosphate (CP) reaction and enable a more rapid resynthesis of CP. This might have enabled the subjects to maintain power output during subsequent high intensity bouts.

Wooton and Williams (1983) had previously found that power output decreased less when either 30 or 60 seconds of active recovery separated the repeated bouts of exercise. However, unlike DH cycling the intermittent protocols used by McMahon and Wenger (1998) and Wooton and Williams (1983) were very uniform in design with pre-determined periods of intense activity and active recovery, always of the same duration. The intermittent bursts in DH racing often vary widely with non-pedalling phases ranging from as little as 5 seconds to 15 seconds at the most. Such short periods of non-pedalling may do little to help recovery and maintain power output from the previous burst of exercise in this type of activity.

Several studies have researched the relationship between $\dot{V}O_{2max}$ and high intensity intermittent exercise and recovery (McCartney *et al.*, 1986; Schreiner, 1988; Rhodes and Twist, 1990; Sleivert, 1991). However, none of these studies employed a training program to investigate the contribution that $\dot{V}O_{2max}$ plays in the recovery from high intensity, intermittent activity. Unlike other studies, Gaiga and Docherty (1995) looked at the effects of a 9-week aerobic interval-training program on performance during short duration intermittent exercise.

Two groups were studied, a training group made up of field hockey players and a control group of sports students. Both groups performed a continuous test of $\dot{V}$

O_{2max} followed by an anaerobic performance test. The anaerobic performance test consisted of four 30 s maximal efforts with 3 minutes recovery between bouts. The training group then followed a 9-week interval-training program. The program involved 30-40 min cycle ergometer sessions made up of 3 min intervals at a HR equal to ~90% $\dot{V}O_{2max}$ separated by 3 min recovery periods. The purpose of the training program was to promote improvements in maximal aerobic power ($\dot{V}O_{2max}$) in order to improve performance during repeated high intensity intermittent activity.

Gaiga and Docherty (1995) reported that following the interval-training program the training group showed significant increases in maximal power output throughout the repeated 30-second efforts. Total work increased by 21.4% and 19.4% for bouts 3 and 4 respectively. The training group also produced significantly greater values than the control group who did not exhibit any significant increases in power throughout the tests. Despite their findings, Gaiga and Docherty (1995) could not be certain that the improvements in performance were the result of improved maximal aerobic power or as a result of some training related aerobic and anaerobic adaptations. Research by MacDougall *et al.* (1998) found that a similar training regime, though with shorter intervals, resulted in increased enzyme activity of hexokinase, phosphofructokinase, citrate synthase, succinate dehydrogenase, and malate dehydrogenase glycolytic. Additionally, maximum short-term power output, and $\dot{V}O_{2max}$ also increased. These results support the suppositions of Gaiga and Docherty (1995) that other interval-training related adaptations may have contributed to their findings.

It is also possible that the improvements reported by Gaiga and Docherty (1995) were caused by a greater familiarisation to the ergometer and the test protocols being used. Prior to the study none of the subjects had previous experience of cycle ergometry therefore an element of learning may have occurred. Martin *et al.* (2000) looked at repeated bouts of maximal power (W_{max}) and the associated learning effects. They found cycle trained athletes could produce reliable results for power output from tests conducted in a single day. However, for active non-cycle trained athletes a minimum of two days of repeated maximal tests were needed for sufficient learning to occur and for results to be reliable. An earlier study by Capriotti *et al.* (1999) also found that a minimum of two familiarisation trials were needed on consecutive days for the results of high intensity tests to be reliable. In addition, they also found that when subjects unfamiliar to these protocols performed two trial tests, results remained valid for up to 6 days after.

This could have a large impact on studies that have tested non-cycle trained athletes on a cycle ergometer, where W_{max} has been used as a dependent variable (Martin *et al.*, 2000). Many of these studies may have significantly underestimated values of power output for athletes, as sufficient time may not have been allowed for adequate learning to occur. This lends support to the idea that the improvements in power output shown by Gaiga and Docherty (1995) may have been, in part, influenced by a learning effect as well as improvements in maximal aerobic power.

Downhill mountain biking is predominantly anaerobic in nature, therefore DH cyclists might benefit more from training the anaerobic system to improve tolerance to lactate accumulation and improve lactate removal, rather than training to improve maximal aerobic power. As DH cyclists rarely pedal for 30 seconds continuously during a race, increasing $\dot{V}O_{2max}$ would potentially do little to aid recovery between maximal efforts of much shorter duration during a race. Improvements in anaerobic capacity might result in an improved ability to sustain power output during repeated high intensity bouts through the improved degradation of muscle glycogen for the resynthesis of creatine phosphate store and more efficient buffering of hydrogen ions that accompany lactate accumulation (Åstrand *et al.*, 2003). However, many DH races are made up of two timed runs, with each rider's fastest run counting. Therefore, it would appear that a combination of improved anaerobic capacity and improved maximal aerobic power could benefit overall performance, as a higher $\dot{V}O_{2max}$ might help speed post race recovery ready for the second timed run.

Power output and high intensity exercise

Research by Padilla *et al.* (2000) examined exercise intensities during competition time trials (TT). During their tests on world-class road cyclists, they recorded W_{max} values of 439 ± 45 W. These values are comparable to those recorded in other studies on elite road cyclists such as that by Padilla, *et al.* (1999), who showed that flat terrain specialists produced W_{max} values of 431.8 ± 42.6W. Balmer *et al.* (2000a) investigated TT performance and the significance of peak power. They found that W_{peak} values derived from a laboratory-based maximal aerobic power test could be successfully used to predict performance power during a 16.1 km TT. Peak power provided a strong indicator of TT performance power over a wide range of abilities (224 to 368 W).

Bentley *et al.* (2001) also looked at power output and TT performances in sub-elite cyclists. They found that W_{peak} was highly correlated (r = 0.91) to performance during a 90 minute TT, as was power at the lactate threshold (W_{LT}) and mean power over the 90 minutes. In contrast, this was found not to be the case during shorter duration TT of 20mins. Bentley *et al.* (2001) reported that performance in shorter TT did not relate to performance in longer duration TT and vice-versa. However, their paper does not provide any explanation for their findings.

Hawley and Noakes (1992) hypothesised that there was a strong relationship between W_{peak} and $\dot{V}O_{2max}$. They also suggested that W_{peak} was a far more reliable and accurate predictor of performance than $\dot{V}O_{2max}$, as a clear 'plateau' or levelling off in $\dot{V}O_2$ often does not occur, thus making accurate prediction of performance harder. Results from tests on trained cyclists showed there was a significant relationship (r = 0.97, $p<0.0001$) between $\dot{V}O_{2max}$ and the W_{peak} a cyclist could sustain during their maximal test protocol. Their study showed that W_{peak} accounted for 94% of variance in $\dot{V}O_{2max}$. As a result $\dot{V}O_{2max}$ could accurately be predicted using the following equation:

$$\dot{V}O_{2max}\,(L.min^{-1}) = 0.01141.W_{peak}\,(W) + 0.435$$

Unlike Bentley *et al.* (2001), Hawley and Noakes (1992) also reported a significant relationship between W_{peak} and 20km time trial performance (r = -0.91, $P<0.001$). Cyclists who elicited a greater sustained W_{peak} produced quicker 20km performances. These differences could be due to the differences in protocols used. Hawley and Noakes (1992) also used a heterogeneous group of highly trained cyclists that included Olympic and Commonwealth Games representatives. Further research would be needed to determine if their findings held true for less trained athletes.

Using the findings of Hawley and Noakes (1992) it would be possible to use W_{peak} to help predict field-based DH performance in the current study. However, peak power alone may not be enough to predict successful performances in DH racing. As DH requires a high degree of technical skill, this should also be assessed in conjunction with W_{peak} to get a more accurate prediction of performance.

Power and the effects of suspension systems

Another area of interest into mountain biking and power output is the effects of different suspension systems. Research by MacRae *et al.* (2000) investigated the differences in physiological responses to uphill cycling when performed on-road and off-road and the effects a front suspension (FS) and dual suspension (DS) mountain bike had on those responses. Results showed that there were no significant differences in ride times or $\dot{V}O_2$ using either of the systems, between the on-road and off-road courses. However, MacRae *et al.* (2000) did find significant differences in average power output for absolute power FS versus DS (266.1 ± 66.6 W vs. 341.9 ± 61.1 W, $p<0.001$) and relative power FS versus DS (2.90 ± 0.55 $W.kg^{-1}$ vs. 3.65 ± 0.53 $W.kg^{-1}$, $p<0.001$) during the off-road tests. Similar results were also observed during the on-road tests.

These differences in power output may be caused due to energy losses through the rear shock resulting in more effort being required to pedal the DS bicycle at the same rate as the FS bicycle. Seifert *et al.* (1997) also found similar results during tests on energy expenditure and time trial performance during mountain biking. The power outputs identified by MacRae *et al.* (2000) were comparable to those of the off-road cyclists studied by Wilber *et al.* (1997). MacRae *et al.* (2000) also concluded that despite the differences in power output using the FS and DS systems this did not have an effect on oxygen cost or performance. The accuracy of their findings could be questioned, as an increase in energy expenditure would generally result in an increase in oxygen cost. The differences in power output observed between the two suspension conditions should have translated to a difference in oxygen cost of approximately 13 $mL.kg^{-1}.min^{-1}$.

Ergometers

Introduction to ergometers

Many physiological assessments now use cycle ergometry, as they can be relatively inexpensive, easy to maintain and are not as cumbersome as treadmills. Cycle ergometers have been used in the physiological assessment of humans as early as Krogh (1913). However, it wasn't until the 1970's that ergometers began to have a significant impact on the assessment of the body's responses and adaptations to exercise. There are many commercially available ergometers on the market; of these the most commonly used ergometers are friction-braked (or mechanically-braked) and air-braked cycle ergometers.

Friction-braked ergometers such as the Monark type (Monark, Varberg, Sweden) consist of a flywheel around which a belt is connected. The belt is attached to a spring and a basket or pendulum where weights are added to increase the tension on the spring. This increase in tension increases the friction on the belt to determine the resistance. A braking force is then applied to the flywheel to determine force. Air-braked ergometers like the Kingcycle (Kingcycle, High Wycombe, UK.) utilise a bladed fan attached to a roller. As speed increases the air resistance against the fan also increases. The flywheel is connected to a photo-optic sensor that measures flywheel velocity. This sensor is attached to a personal computer that converts the electrical signal from the flywheel into a power value.

Over the past few years the development of mobile power measuring systems has made the field-testing of power output possible. One of the most popular mobile measuring devices, and most accurate according to much of the current literature available, is the SRM Powermeter (Schoberer Rad Messetechnik, Jüllich, Germany). This system is available in several versions each using a different number of strain gauges to record power. Table 2 lists each version of the Powermeter and the number of gauges used.

	Amateur Version	**Professional Version**	**Scientific Version**
Power Accuracy	± 5%	± 2%	± 0.5%
Crank Options	Road	Road, Mountain Bike (MTB), Track	Road, Track
No. Gauges	2	4	20

Table 2. SRM Powermeter Options.

Strain gauges are attached to the inside of a disk situated within the inner bolt circle of the crank arm. As force is applied to the cranks the gauges measure the movement of the metal and convert this into a power value proportional to the pedal force. This signal is then transmitted to a handlebar mounted power controller that interfaces with the cranks via a wired receiver and magnet mounted on the bottom bracket unit of the bicycle. From the power controller data such as power output, cadence, speed and heart rate can be downloaded to a personal computer.

One of the newest mobile systems for recording field-based power output is the Polar S710 heart rate monitor (Polar, Kempele, Finland). This monitor is available with an additional power sensor kit that fits to most conventional bicycle frames. Unlike the SRM system, which measures power through torque and angular velocity, the Polar system works by measuring chain tension via a sensor mounted to the lower jockey wheel of the rear derailleur and a chainstay mounted sensor that calculates chain vibration and chain speed. Power is then calculated using the equation:

$$\text{Power} = \text{Chain tension} \times \text{Chain speed}$$

Additionally, the S710 employs a third sensor mounted to the left-hand chainstay that records wheel speed and distance. The three sensors are then connected to a battery on the handlebars, which in turn holds the watch/receiver.

Validity of ergometers and power measuring devices

To maintain reliability and accuracy all ergometers and power measuring devices need to be re-calibrated periodically. Van Praagh *et al.* (1992) recognised the need for the regular calibration of ergometers and devised a simple method for the calibration of fiction-braked cycle ergometers. With the cranks being replaced by a pulley, velocity was increased and for each increase in velocity a braking force was applied. The relationship between pulley force and acceleration were linear and extrapolated for zero acceleration in order to determine the 'limit-force'.

All cycle ergometers should be within a five percent margin of error in order to provide a valid and reliable measure of power output (Van Praagh *et al.*, 1992). They compared the actual force measured with the proposed values of the manufacturer and found that as force increased the errors decreased from 9.6% at 30 W to 2.9% at 60 W for a speed of 60 revs.min^{-1}.

Van Praagh *et al.* (1992) demonstrated that as power output increased the friction-braked ergometer tested in their study fell within their own recommended 5 percent margin of error. However, at lower power outputs it was outside this margin and therefore did not provide a valid measure of power at lower levels. Though their calibration method may have been simple and inexpensive it did highlight the inaccuracies of friction-braked ergometer at low power outputs.

A later study by Woods *et al.* (1994) argued that although the calibration method of Van Praagh *et al.* (1992) was simple, it did not allow for the continued monitoring of power output. The calibration method of Van Praagh *et al.* (1992) also only looked at power up to 60W. Despite this they claimed their method was accurate for higher power output also. This assumption could lead to inaccurate results when used during high intensity activities such as DH.

Woods *et al.* (1994) also pointed out that when friction-braked ergometers are calibrated statically by suspending weights at the point of belt attachment, frictional resistance is often ignored. They also stated that frictional resistance can lead to power output being increased by approximately 9 percent above that calculated from braking force and cadence alone. Winter (1991) also reported the need for frictional resistance to be taken into account and suggested a correction factor in the order of 9 percent also.

Paton and Hopkins (2001) found that the pendulum version of the Monark cycle ergometer underestimated power by ~5 percent at workloads of ~300 W. At lower power outputs these errors were found to be greater still. They also attributed these errors to frictional losses in the drive chain connecting the cranks to the flywheel. Paton and Hopkins (2001) stated that other random errors in measurement might be due to inaccuracies in reading the load on the pendulum and the build up of heat between the flywheel and the belt. As a result, Paton and Hopkins (2001) disagreed that the Monark cycle ergometer is the "Gold Standard" in ergometer testing as suggested by Martin *et al.* (1998). Paton and Hopkins (2001) believe that whether using the basket or pendulum version of the Monark, there will always be frictional losses present that will result in errors in power measurement. Like the Monark ergometer, the Polar S710 tested in the present study is a chain driven system, therefore it will potentially suffer from similar frictional losses through the drive system of the test bicycle.

Paton and Hopkins (2001) like Van Praagh *et al.* (1992), again looked at relatively low power outputs when compared to those produced during all out cycling activity and used continuous protocols to investigate agreement. This again highlights the need for research into assessment methods for high power intermittent activity.

Air-braked ergometers are also commonly used in sport science laboratories and training centres. Palmer *et al.* (1996) looked at the reliability and reproducibility of performance testing on the popular Kingcycle air-braked ergometer. They evaluated simulated 20km and 40km TT on the Kingcycle and found the test-retest reproducibility was high, indicated by the small group co-efficient of variation, 1.1 ± 0.9% and 1.0 ± 0.5% for 20km and 40km TT respectively. Palmer *et al.* (1996) also noted a high correlation between simulated 40km TT and actual 40km TT times thus further supporting the validity of the Kingcycle system for accurate prediction of performance. They believed one of the major advantages the Kingcycle system has over other ergometer systems is that it allows subjects to use their own racing cycle and can therefore simulate more closely their actual racing position.

Despite the widespread use of air-braked ergometers and the findings of Palmer *et al.* (1996) air-braked ergometers are susceptible to environmental changes in air pressure, temperature and humidity (Paton and Hopkins, 2001). Research by Finn *et al.* (2000) evaluated the effects these environmental variables had on the validity of power output of air-braked cycle ergometers. Their results found that power output increased 1 percent for an increase in temperature of 2.7°C or a decrease in air pressure of 7.6mmHg. Power is also affected by humidity but to a lesser extent. An increase in humidity of 10 percent only increases power output by 0.1 %. Of all the environmental variables barometric pressure has the greatest effect on air-braked ergometers (Finn *et al.*, 2000).

Finn *et al.* (2000) found that as altitude increased and air pressure decreased the validity of power output from air-braked ergometers also decreased. However, they noted that when correction factors were applied to account for the changes in environmental conditions the ergometers were accurate to within 3 percent of true power (range 1.7-4.4 ± 0.7 %). As a result, Finn *et al.* (2000) concluded that between altitudes of 38m and 1800m above sea level air-braked ergometers could provide a valid measure of power output provided correction factors were taken into account.

Research by Balmer *et al.* (2000b) also looked at the validity of power output recorded using the Kingcycle ergometer when compared to the SRM Powermeter. Jones and Passfield (1998) had previously determined that the SRM Powermeter provided a reliable means of recording power. They found no significant variations in two different pairs of cranks of 20 gauge and one 4 gauge Powermeter. When compared to a motor driven Monark ergometer the SRM's overestimated power by only ~1 % at high power outputs. This difference was attributed to friction losses in the Monarks' drive chain.

Balmer *et al.* (2000b) looked at peak and average power during a 16.1km TT between the Kingcycle and SRM systems. Their findings showed that power recorded by the Kingcycle was significantly greater than that of the SRM Powermeter during an incremental test (443 ± 65 W and 399 ± 54 W respectively). The same was observed during the TT (335 ± 18 W and 307 ± 19 W) for the Kingcycle and SRM Powermeter respectively. Balmer *et al.* (2000b) also found that the differences in power recorded were greater still at higher power outputs and that this was up to 10 percent between the two systems.

In contrast to the findings of Palmer *et al.* (1996), Balmer *et al.* (2000b) disagreed that the Kingcycle provides a valid measure of power as their results showed it did not fall within a five percent margin of error. They went on to state that the Kingcycle is too reliant on other variables such as tyre pressure as well as the environmental conditions. Further errors can arise using the Kingcycle due to wheel slippage. This is most apparent during maximal testing.

Another study that analysed the validity of the SRM Powermeter was that of Lawton *et al.* (1999). They used dynamic calibration to validate 19 SRM Powermeters (professional version). SRM claim this version of their system to be accurate to within ± 2 %. Lawton *et al.* (1999) tested each pair of cranks against a calibration rig over a range of 50-900 W. Results showed that mean percent error equalled 2.5 ± 5.0 %. However, Lawton *et al.* (1999) reported that four pairs of the cranks showed errors of 9-10 %. Despite the higher errors in four of the cranks Lawton *et al.* (1999) believe the SRM is a reliable measure of power output.

The current crop of literature pertaining to the validity of ergometers point to the SRM Powermeter as setting a new standard in accuracy both in the laboratory and out in the field. However, most of these studies have only tested the accuracy of the SRM system under continuous conditions. The present study aims to evaluate how valid the system is when used to measure power output during high intensity discontinuous activity as used in DH.

A recent study by Millet *et al.* (2003) compared the validity and reliability of the Polar S710 to the SRM system during continuous activity. Their research looked at power output at 60 %, 75 % and 90 % of subjects peak power output and at cadences of 60, 90 and 110 revs.min^{-1}. The chosen cadences were reflective of those used during hill climbing, flat racing and track racing respectively. Millet *et al.* (2003) found that during field tests the S710 recorded mean power (W_{mean}) higher than the SRM by 7.4 ± 5.1% and by 6.8 ± 7.9% during laboratory conditions. Their study also showed that as exercise intensity increased so did the differences in power readings.

Hypotheses

As can be seen from the preceding review of literature, there has been much research conducted into the performance dynamics of cycling in particular road cycling and cross-country mountain biking. However, a profile for Downhill mountain biking has yet to be established. The purpose of the current study was to provide details of the field-based power characteristics of DH mountain biking and to identify the best methods of assessing this. The research was subsequently divided into two separate investigations.

Study one was laboratory based and aimed to determine the most accurate method of recording power output during high intensity intermittent cycling activity of a DH nature. With the SRM Powermeter being used as the criterion measure, it was hypothesised that there would be no significant differences in power recorded by the two measuring devices during an intermittent protocol to simulate a typical DH race. Any observed differences would fall within the 5 % error limits proposed by

Van Praagh *et al.* (1992) and therefore both systems would provide a valid means of measuring power output. Additionally, study one also sought to confirm the validity of the SRM and Polar S710 during continuous cycling activity. It was again hypothesised that both systems would provide a valid measure of power output with any difference between measured values falling within the 5 % error limits.

Study two had two purposes. The first was to record and identify the power characteristics of field-based DH mountain biking employing the best assessment method identified in study one. At approximately 3 minutes in duration a typical UK DH race falls between 1 km and 4 km track TT's times. It was therefore hypothesised that peak power would be between 1799 W and 1100 W as reported by Craig and Norton (2001) and Broker *et al.* (1999) for 1 km and 4 km TT respectively. Mean power for the DH runs would be between 600-750 W, again between those values recorded for 4 km and 1 km TT respectively. Additionally, it was hypothesised that cadence for the field-based DH tests would be greater than 120 revs.min^{-1} and comparable to those of sprint cyclists studied by Van Soest and Casius (2000).

The second aim of study two was to compare values for power, cadence and heart rates between the field-based tests and the laboratory intermittent tests. It was hypothesised that values for these variables would be of a similar magnitude between the two test conditions as the laboratory intermittent test was designed to simulate a typical DH race as closely as possible and was developed from observations and video analysis of the course used for the field tests.

CHAPTER THREE – METHODOLOGIES

Study One (Laboratory tests)

Participants

Twelve male participants performed a laboratory-based intermittent maximal test and a continuous incremental ramp test to determine agreement between the two ergometers. Subjects included downhill cyclists ($N = 4$), cross-country cyclists ($N = 4$) and road cyclists ($N = 4$). The heterogeneous nature of the subjects was sought to provide power values over a wide range during both tests. All subjects participated in their respective disciplines on a regular basis (at least three times per week) and ranged in abilities from 'Sport Class' (DH and XC) or 'Category 4' (RD) to 'Elite' (DH and RD) with one DH and one RD cyclist having represented Great Britain at international level.

In addition to the main tests, anthropometric measurements were also taken for each subject. Stature was measured using a stadiometer (Harpenden, Avery Ltd, Birmingham, UK) to the nearest 0.001 m. Body mass was weighed using balance beam scales (Avery Type 3306, Avery Ltd, Birmingham, UK). Skinfold measurements were taken from seven sites (Pectoral, midaxillary, abdominal, suprailium, subscapular, triceps and midthigh) using skinfold callipers (Harpenden, Body Care, Kenilworth, UK). Using the sum of the seven skinfolds, percentage body fat was estimated using the prediction equation of Jackson and Pollock (1978). This equation was chosen as it took into account the lower limbs of the body.

To facilitate the prediction of percentage muscle mass the prediction equation of Martin *et al.* (1990) was employed, with girth measurements being taken at the midcalf, and at the widest point on the forearm. Additionally, further skinfolds were taken at the midcalf. All body composition measurements were performed using the guidelines of Lohman *et al.* (1988).

Upon approval by the University of Central Lancashire Ethics Committee, all subjects were informed both verbally and in writing of the test procedures and written informed consent was obtained (see appendices A and B). Subjects also completed the University of Central Lancashire Sports Science laboratory health-screening questionnaire prior to testing (see appendix c). All subjects refrained from exercise for a period of 24 hours before testing, and refrained from eating for a period of 2 hours pre-test. Tests were conducted with a one-week rest period separating each, at the same time of day.

Materials and equipment

All laboratory tests for the intermittent and continuous tests were performed on a 48.3cm framed Nirve HTX 2 (Paligap Ltd., UK) mountain bike with a standard double triangle shape frame design. The test bicycle was fitted with an SRM MTB Powermeter system with a crank length of 175mm (Schoberer Rad Messetechnik, Jüllich, Germany) incorporating four stain gauges. A Powercontrol meter was mounted onto the handlebar and interfaced with the Powermeter via a wired receiver and magnet mounted on the bottom bracket shell. The validity of the SRM has been well documented (Jones and Passfield, 1998; Lawton *et al.*, 1999) therefore it was used as the criterion measure of power output during the tests.

The test bicycle was also fitted with the Polar S710 heart rate monitor and power sensor kit (Polar, Kempele, Finland) to allow for the simultaneous assessment of power via both ergometer systems. The power sensor was positioned on the right-hand chainstay while a chain speed sensor was bolted to the lower jockey wheel of the rear derailleur. A magnet was attached to the side of the right crank arm to allow transmission of the signals. Additionally, the S710 employs a third sensor mounted to the left-hand chainstay to record speed. The three sensors were then connected to a battery on the handlebars, which in turn held the receiver/watch unit. As the Polar system used coded transmission and a frequency of 5 kHz and the SRM transmitted data at 500 kHz the risk of 'cross-talk' between the two ergometers was minimal.

The rear wheel of the test bicycle was fitted with a slick tyre to reduce resistance between itself and the flywheel of the Kingcycle. The bicycle was then mounted onto a Kingcycle ergometer (Kingcycle, High Wycombe, UK). The Kingcycle set up and calibration procedure was followed to ensure correct tyre contact with the flywheel, however, this was used only as a mount for the bicycle to sit on and was not used for comparison with the SRM and Polar systems due to the Kingcycle's susceptibility to errors in the measurement of power output, as discussed in chapter two.

Oxygen uptake was monitored and recorded using an automated gas analysis system (Jaeger Oxycon Delta, Viasys, UK). Expired gases were collected via a facemask and a bi-directional digital volume sensor. Data from the Oxycon Delta, SRM and Polar systems were downloaded to a personal computer for further analysis. Subjects were allowed to use their own pedals and saddle. Height and reach were adjusted to match as closely as possible the subjects own bicycle, with a variety of stems and seat posts available for adjustment. In accordance to the manufacturers' guidelines, a zero offset was performed for the SRM Powermeter prior to each test. The zero offset is the amount of strain generated by the cranks themselves without any pressure being applied to the pedals. This value is affected by temperature and tension on the cranks, therefore the procedure must be performed prior to each use in order to minimise errors.

Intermittent test protocol

The intermittent protocol used, aimed to closely simulate a UK downhill mountain bike race, which is typically 3 minutes in duration. The order and duration of each effort and rest period was determined following video analysis of a downhill race. This analysis involved the video recording of five downhillers over a typical DH course. Six video cameras were set up at various points along the course. The decision to use six cameras was dictated by equipment availability. Had more cameras been available they would have been used. Despite this limitation the use of 6 cameras enabled the video capture of approximately 80 % of the test course. This was also aided by the lack of tree coverage along the course. From the video captures an average profile for pedalling versus rest was created, this can be seen in figure 4.

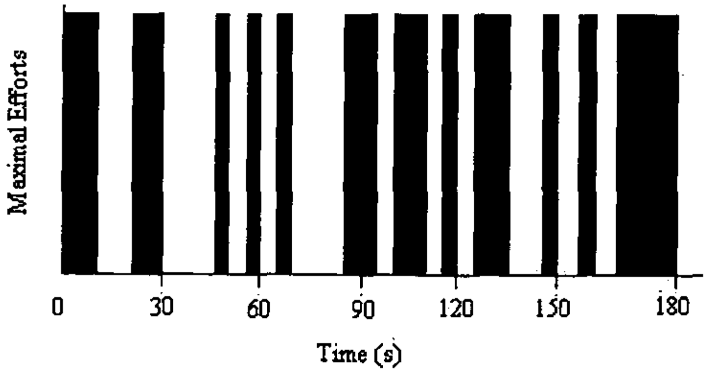

Figure 4. Pedal to rest profile of the intermittent test protocol. (Bars represent the varying duration of each maximal effort, while the gaps indicate the duration of each non-pedalling period).

The reliability of the intermittent tests were assessed using Cronbach's Alpha Coefficient with both systems (r = 0.89 and 0.94 for S710 and SRM respectively). The course used for video analysis was 1.7km in length, with a vertical interval of 174m. Starting elevation was 357 metres. The same course was also used for field-testing, a profile of the course is outlined in figure 5. This profile was provided by the course owners and was determined using a Global Positioning Satellite system (GPS). Composed mainly of fast open tracks and technical single-track trails, the course was also interspersed with obstacles including two near-vertical drops of over three metres in height, cattle grids and man-made jumps. In addition, a short (<50m) section of switchbacks were also encountered.

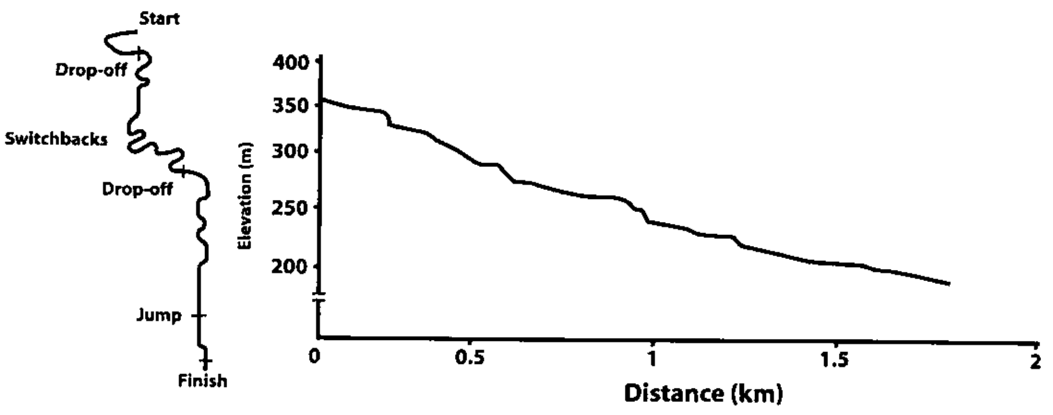

Figure 5. Schematic of course profile and vertical descent (m) of the downhill course.

Prior to the tests subjects performed a five-minute, self-paced warm up. They were then allowed to undertake dynamic flexibility activities and perform several starts in order to select an appropriate gear ratio to perform the test. Subjects then rested for 3 minutes. Agreement between the two systems was determined through the analysis of power output.

Subjects were given two commands. On the 'Go' command subjects were instructed to pedal as hard and as fast as possible until they received the 'Stop' command, at which point they were required to stop pedalling completely. The complete cessation of effort was to simulate the non-pedalling phases of DH cycling. Subjects remained in a seated position throughout the test in order to minimise lateral movement of the test bicycle caused by upper body muscle contribution. A full description of each effort/rest duration can be seen in appendix D.

The Polar system was set to its' optimal sampling frequency of five seconds while the SRM was set to a record interval of one second. Though record intervals of 0.25 seconds were possible with the SRM they would have yielded little difference in values for power. For each effort W_{peak} was recorded by each system and W_{mean} was calculated for the overall test. In addition to power measurement, cadence was also recorded by both systems.

Heart rate was recorded using a short-range telemetry system (S710, Polar, Kempele, Finland), set to record at five-second intervals. Chest straps were placed inferiorly to the xiphosternal joint. Age predicted heart rate was determined using the equation of Tanaka *et al.* (2001). Oxygen uptake ($\dot{V}O_2$) was recorded at 5-second intervals throughout the test by a Jaeger Oxycon Delta gas analyser.

Continuous incremental test protocol

As with the intermittent protocol, subjects performed a five-minute self-paced warm up prior to starting the incremental test. Starting intensity was 125 W and was increased by 35W every 2 minutes. Subjects were required to maintain a pedalling cadence of 80 – 90 $revs.min^{-1}$.

An increase in $\dot{V}O_2$ of ≤ 2 mL.kg^{-1}.min^{-1}, the achievement of the subjects age defined maximum heart rate or a respiratory exchange ratio (RER) of >1.15 was used as the criteria to terminate the test. Maximal oxygen uptake was then calculated as the 30 s average for the last completed stage. Values were averaged between the 60 s and 90 s for each stage. Mean power output was also determined for the test. Respiratory parameters were again recorded at five-second intervals. Heart rate was recorded using the S710 heart rate monitor at 15 s intervals. Age predicted heart rate was again determined using the equation of Tanaka *et al.* (2001). Power output was recorded at 15-second intervals by both the SRM and Polar S710 ergometers. Peak power output was taken as the highest value during the last 30 s period used to calculate $\dot{V}O_{2max}$. Again reliability of the test was assessed using Cronbach's Alpha Coefficient ($r = 0.95$ and 0.99 for the S710 and SRM respectively).

Study Two (Field tests)

Participants

The present study also aimed to examine the power characteristics of field-based DH riding. Accordingly, seventeen male participants took part in field-based testing. All subjects were national level downhill mountain bikers, and competed on a regular basis. Subjects for the field tests trained using a combination of downhill and cross-country modalities, to a ratio of 3:1. Again, anthropometric measurements were taken following the procedures outlined for the laboratory tests. Written informed consent was gained and subjects were again instructed to refrain from exercise for a period of 24 hours before testing, and to refrain from eating for a period of 2 hours pre-test.

Materials and Equipment

During field tests all subjects performed their runs using the same 43.2cm frame, single pivot full suspension downhill bike (Sintesi, Italy). The bicycle had suspension dampening set at 16.8 cm of travel for the front and rear shock units. The field test bicycle was fitted with the SRM Powermeter as shown in figure 6. As a result of the laboratory testing the Polar S710 ergometer was not used during field-testing to monitor power output. However, the S710 transmitter and watch receiver was used to record heart rates. All subjects opted to run a 42-tooth chainring.

Subjects wore a protective 'armoured' jacket consisting of torso, spine and full length arm padding and a kidney belt, along with padded trousers during field-testing. Additionally, shin pads were also used. In accordance to DH governing body regulations, all riders were required to wear a full-face protective helmet and gloves. A selection of seat posts and stems were again available to ensure best fit for riders. Of the 17 riders, 14 chose to use 'clip-in' pedals similar in design to those used by road cyclists. Only three riders chose to use flat 'BMX' style pedals, with no restraint system. Again, a zero offset was performed for the SRM Powermeter prior to each test run.

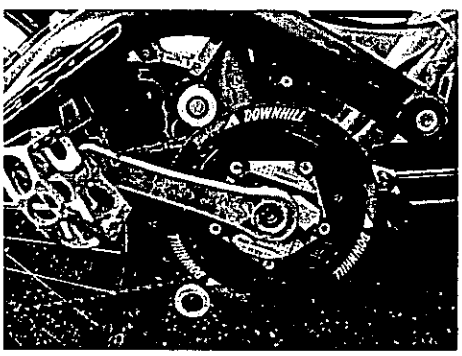

Figure 6. Field-test bicycle fitted with an SRM Powermeter and a chain retention device.

Field test protocol

All field tests took place on the same course used during video analysis to determine the laboratory-based intermittent test protocol. The chosen test course is currently used on the UK race circuit and is typically representative of courses used in the UK. For the field tests, the SRM Powermeter system was set to record at one second intervals. Times for the runs were also recorded using the SRM using the stopwatch function. The SRM Powermeter was attached to the test bike through a downhill specific chain retention device. Chain 'slip' is a common concern for downhill cyclists, and these devices provide a measure of security to prevent this occurrence. An example of a chain device can be seen in figure 6.

Power output was recorded as the mean and peak values measured during the test runs. As an adjunct to power measurement the SRM system also allowed the recording of cadence and speed. Again, values are expressed as the average and peak values measured during the runs. Heart rate was recorded at 5 s intervals as described previously in the intermittent laboratory protocol.

Subjects completed a two stage warm up consisting of dynamic flexibility activities and large muscle group activities aimed at elevating the heart rate. In addition, riders undertook a pre-test familiarisation session involving a 'walk down' of the route and 2 practice runs. Riders then performed two timed runs separated by a 2 h rest period. Each rider's quickest run was used for analysis. The SRM system was set to record from five seconds prior to the start of the test run. On the command "3, 2, 1, GO" subjects left the designated start gate. Following completion of the test run, recording was stopped within 10 seconds. All tests occurred under dry course conditions. Cronbach's Alpha Coefficient was once again used to determine the reliability of the field tests ($r = 0.95$).

Statistical analyses

Descriptive data were generated using the SPSS statistical software package (SPSS Inc., version 12.0, Chicago, Illinois). Data were tested for normal distribution using a histogram. For the intermittent and continuous tests statistical differences between the means for the two ergometers were analysed using a paired student's *t*-test. Differences between the power output measurements recorded with the SRM and S710 were compared using 95% ratio limits of agreement (Bland and Altman, 1986; Atkinson and Nevill, 1998). The differences between the two measures were plotted against the mean values and analysed for heteroscedasticity for each test. Where this was evident, data were log transformed to calculate the ratio limits of agreement. Any zero values recorded by either system during the laboratory tests were eliminated for statistical analysis.

For the field tests mean and standard deviation scores were calculated for average and peak power output, cadence, speed and heart rate. Time to peak power was also recorded. The range of scores measured was also identified. Relationships between field test variables were identified using the Pearson's Product Moment correlation coefficient. SPSS was again used for statistical analysis. Significance levels were set at $p<0.05$ for all tests. All subjects recorded zero values for both power and cadence during non-pedalling phases of the field tests. Therefore, mean power and cadence values were calculated with the zero values included and excluded, as these non-pedalling phases were an important contribution to the field runs. The data from both calculations are presented in the results section. All results are presented as mean ± standard deviation (s.d.) or else stated otherwise.

CHAPTER FOUR – RESULTS

Physiological and anthropometric characteristics

A one-way ANOVA with Scheffe post hoc analysis was used to determine anthropometric differences between the three laboratory groups. The results found no significant differences for all variables. As a result of this homogeneity one large laboratory group was formed. A paired student's *t*-test was subsequently used to determine significant differences in anthropometry for the laboratory and field groups. Table 3 summarises the anthropometric characteristics of the laboratory and field groups. Body composition analysis revealed no significant differences between the two groups ($p < 0.05$) for stature $p = 0.96$, body mass $p = 0.97$, %BF $p = 0.72$, muscle mass $p = 0.93$ and %muscle mass $p = 0.95$.

	Laboratory Group	**Field Group**
Age	31.4 ± 9.8	27.1 ± 5.1
Stature (cm)	180 ± 8.1	179 ± 1
Body Mass (kg)	77.7 ± 8.1	77.6 ± 6.9
% Body Fat	10.7 ± 4.2	7.1 ± 2.0
Muscle Mass (kg)	45.1± 6.1	45.8 ± 3.5
% Muscle Mass	58.1 ± 4.1	58.9 ± 3.3

Table 3. Physiological characteristics of subjects. (Values are mean ± standard deviation).

Mean peak oxygen uptake ($\dot{V}O_{2peak}$) for the continuous test was 61.63 ± 7.3 $mL.kg^{-1}.min^{-1}$ (range 50.40 to 78.20 $mL.kg^{-1}.min^{-1}$), whilst $\dot{V}O_{2peak}$ for the intermittent test was 54.20 ± 6.6 $mL.kg^{-1}.min^{-1}$ (range 42.0 to 61.1 $mL.kg^{-1}.min^{-1}$). Peak oxygen uptake during the intermittent test equated to 88 % of the $\dot{V}O_{2peak}$ attained during the continuous test. Figure 7 shows $\dot{V}O_{2peak}$ for each subject during the continuous and intermittent tests.

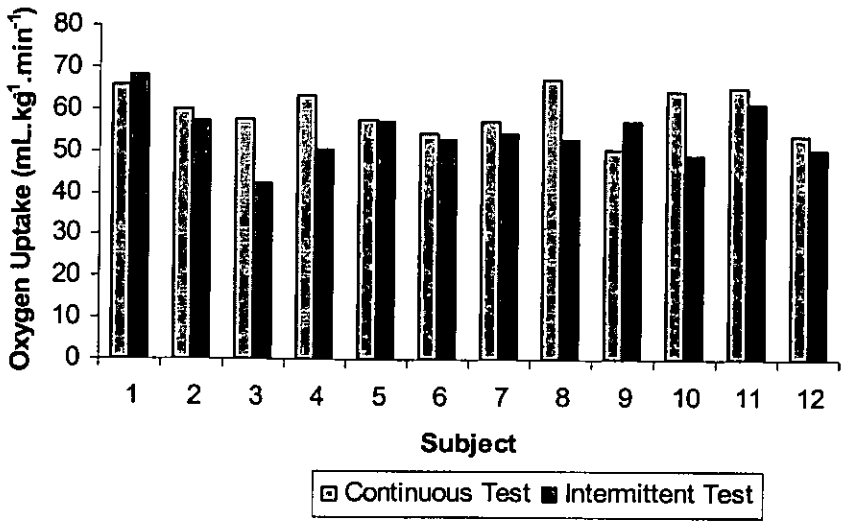

Figure 7. Peak Oxygen uptake during continuous and intermittent tests for each subject.

Intermittent test

Power output

Mean power over the twelve intervals was 556 ± 102 W (range 409 to 641 W) and 446 ± 61 W (range 361 to 590 W) for the SRM and S710 respectively. Peak power was 737 ± 135 W (range 498 to 995 W) and 601 ± 76 W (range 467 to 736 W) for the SRM and S710 respectively. When adjusted for body mass, peak power was 9.50 ± 1.45 $W.kg^{-1}$ and 7.84 ± 1.35 $W.kg^{-1}$ recorded using the SRM and S710 respectively. Figure 8 shows the mean power values calculated for each of the twelve maximal effort intervals of the intermittent test.

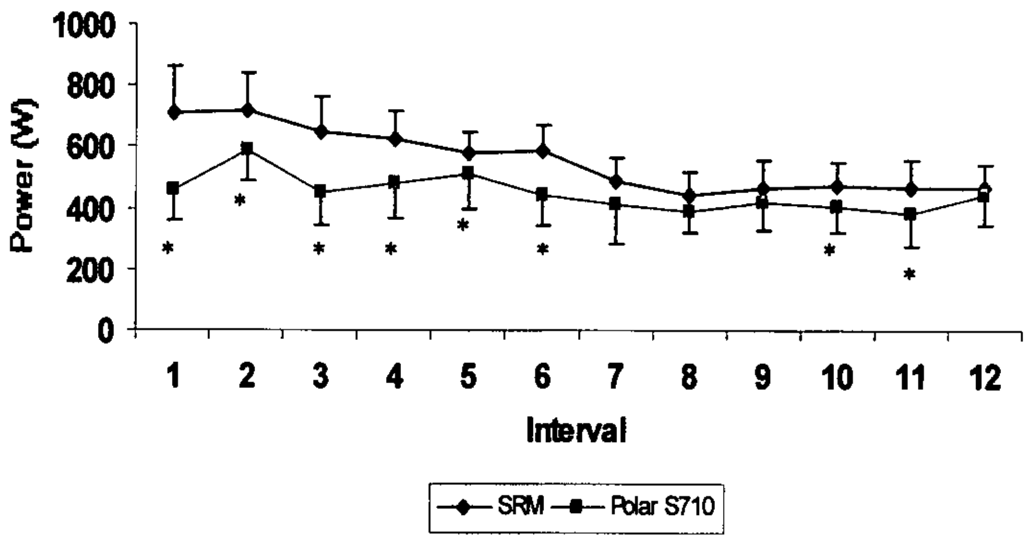

Figure 8. Mean power values recorded at each interval during the intermittent test. (*) indicates significant differences in values.

The intermittent test also revealed significant differences ($p<0.05$) between power values recorded by the S710 and SRM cycle ergometer systems. These differences occurred at eight of the twelve intervals, with intervals 7, 8, 9 and 12 showing no significant difference in values. A significant difference ($p=0.001$) was also found between the SRM and S710 when mean power was averaged over all twelve intervals. Data were found to be heteroscedastic.

Table 4 shows the bias, random error and 95 % limits of agreement (Atkinson and Nevill, 1998) for the S710 and SRM. Analysis of the ratio bias revealed that on average the S710 system underestimated power by 23% when compared to the SRM Powermeter. The random error between the two systems was in the range of */÷ 24% (95 % limits of agreement being 0.99-1.53). The results also revealed increases in bias at intervals 3, 6 and 10 (bias =1.46, 1.36 and 1.18 respectively) over the previous interval. The median random error was 51%, while the minimum and maximum error values were 36% and 141% respectively. Mean and standard deviation values for SRM and S710 W_{peak} at each interval can be found in appendix G.

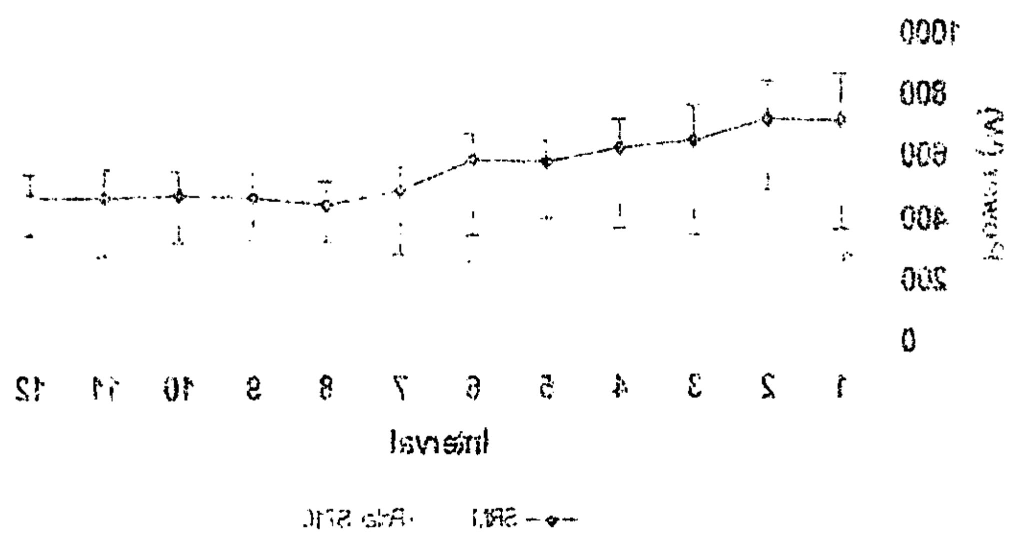

Figure 8. Mean power values recorded at each interval during the intermittent test. (*) indicates significant differences in values.

The intermittent test also revealed significant differences ($p < 0.05$) between power values recorded by the S710 and SRM cycle ergometer systems. These differences occurred at eight of the twelve intervals, with intervals 7, 8, 9 and 12 showing no significant difference in values. A significant difference ($p < 0.001$) was also found between the SRM and S710 when mean power was averaged over all twelve intervals. Data were found to be heteroscedastic.

Table 4 shows the bias, random error and 95 % limits of agreement (Atkinson and Nevill, 1998) for the S710 and SRM. Analysis of the ratio bias revealed that on average the S710 system underestimated power by 25% when compared to the SRM Powermeter. The random error between the two systems was in the range of [illegible] – 24% (95 % limits of agreement being 0.99-1.53). The results also revealed increases in bias at intervals 3, 6 and 10 (bias = 1.46, 1.30 and 1.18 respectively) over the previous interval. The median random error was 51%, while the minimum and maximum error values were 16% and 141% respectively. Mean and standard deviation values for SRM and S710 W_{avg} at each interval can be found in appendix G.

Interval	Polar S710 to SRM power Bias	Random error	95% limits
1	1.55	*/÷ 1.88	0.83-2.91
2	1.22	*/÷ 1.67	0.73-2.04
3	1.46	*/÷ 1.91	0.76-2.79
4	1.30	*/÷ 1.51	0.86-1.96
5	1.15	*/÷ 1.36	0.85-1.56
6	1.36	*/÷ 1.57	0.87-2.14
7	1.26	*/÷ 2.41	0.52-3.04
8	1.13	*/÷ 1.51	0.75-1.71
9	1.12	*/÷ 1.50	0.75-1.68
10	1.18	*/÷ 1.40	0.84-1.65
11	1.13	*/÷ 1.40	0.81-1.58
12	1.06	*/÷ 1.50	0.71-1.59
Mean	1.23	*/÷ 1.24	0.99-1.53

Table 4. Bias, random error and 95% limits of agreement for Polar S710 and SRM Powermeter power recorded during the 3-minute intermittent test using ratio values.

The Bland-Altman plot in figure 9 revealed a degree of agreement between the SRM and S710 at lower power outputs. However, the plot also revealed the heteroscedastic nature of the data as agreement between measures deteriorated as power output increased. Ninety five percent of the recorded values ranged between –18.16 W and 238.71 W. The differences between the measures are greater with the highest power outputs. Reliability of the intermittent tests was $r = 0.89$ and $r = 0.94$ using the S710 and SRM respectively.

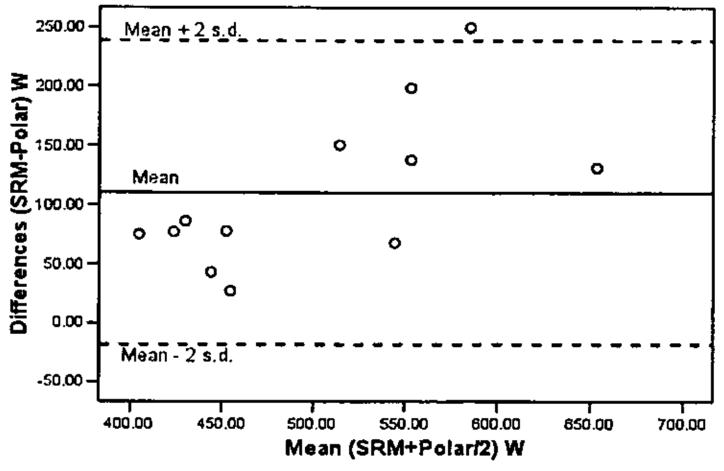

Figure 9. Bland-Altman plot of mean peak power output against the differences between power output values recorded by the SRM and Polar S710 power meters for the incremental tests.

Heart rate

Age-predicted maximum heart rate (HR_{max}) was 188 ± 10 beats.min^{-1}. Mean heart rate during the intermittent test was 155 ± 7 beats.min^{-1} (range 148 to 168 beats.min^{-1}). This equated to 82% of age-predicted HR_{max}. Mean heart rates during the intermittent test are presented in figure 10. Mean and standard deviation values for each 5 s interval can be found in appendix H.

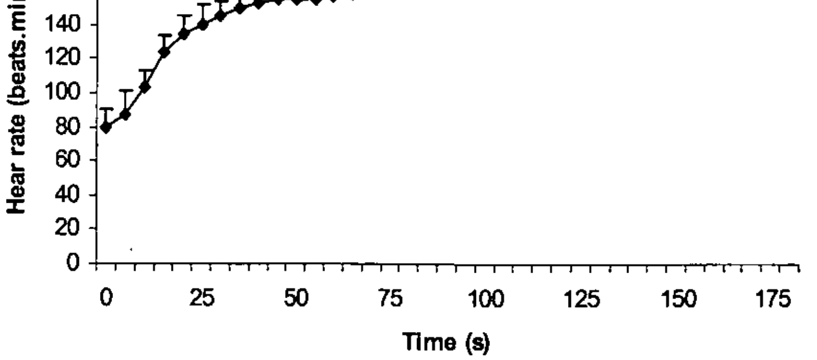

Figure 10. Mean heart rate recorded at 5-second intervals with the S710 heart rate monitor during the intermittent test.

Cadence

Average cadence for the intermittent tests was 117 ± 8 revs.min^{-1} (range 107 to 135 revs.min^{-1}) and 106 ± 11 revs.min^{-1} (range 88 to 125 revs.min^{-1}) for the SRM and S710 respectively. Peak cadences recorded using the SRM and S710 were 136 ± 15 revs.min^{-1} (range 117 to 156 revs.min^{-1}) and 129 ± 15 revs.min^{-1} (range 99 to 156 revs.min^{-1}) respectively. Mean cadences values recorded by the two systems are presented in figure 11. Mean and standard deviation values for each 5 s interval can be found in appendix I for each system.

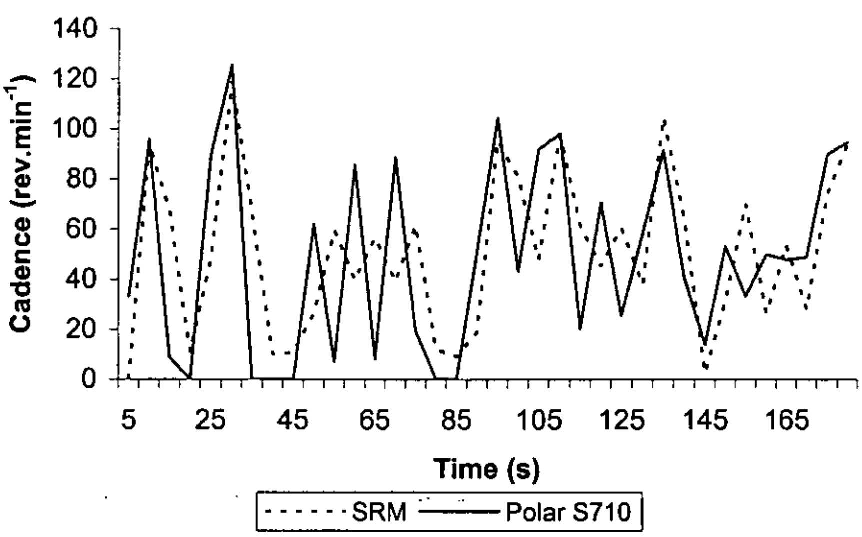

Figure 11. Mean cadence values for the SRM and Polar S710 recorded during the intermittent test.

Significant differences (p=0.014) were present between the two systems when cadence was averaged over the duration of the test. However, no significant differences were found at any of the individual intervals.

Continuous test

Power output

Mean power output over the duration of the continuous incremental test was 189 ± 51 W (range 156 to 225 W) and 212 ± 49 W (range 179 to 242 W) for the SRM and S710 respectively. Peak power output was taken as the highest value during the last 30 s period used to calculate $\dot{V}O_{2max}$. The average W_{peak} was 270 ± 41 W (range 222 to 346 W) and 305 ± 67 W (range 248 to 462 W) for the SRM and S710 respectively. The mean time to W_{peak} and subsequently $\dot{V}O_{2peak}$ was 10.59 ± 1.65 mins^{-1} (range 8.05 to 13.40 mins^{-1}). Figure 12 shows the mean power values recorded at each increment by both systems test.

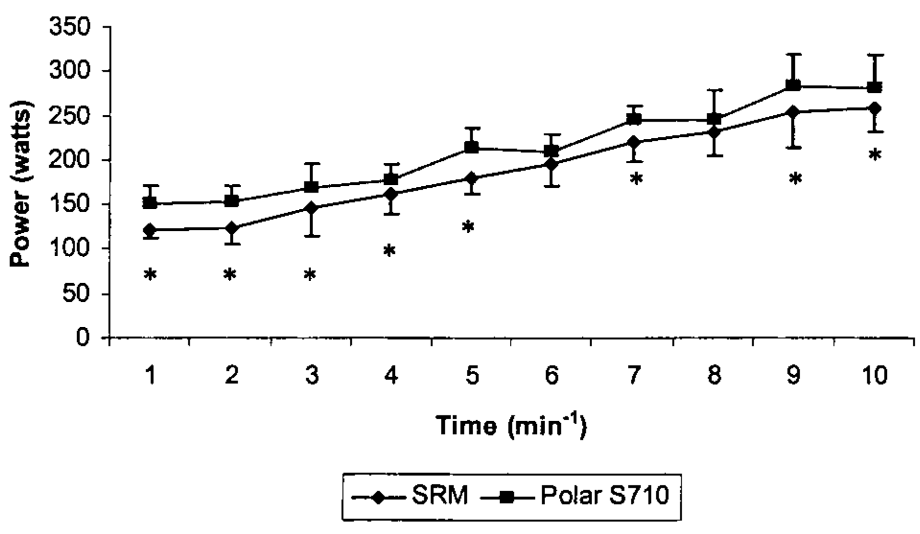

Figure 12. Mean power values record during the incremental ramp test. (*) indicates significant differences between values.

Power output recorded by the Polar S710 was significantly higher (p<0.001) by 12% (23 ± 7 W) than power values recorded when using the SRM Powermeter system. Significant differences are also presented in figure 12.

Table 5 shows the bias, random error and 95% limits of agreement (Atkinson and Nevill, 1998) calculated for the S710 and SRM Powermeter during the incremental test. Data were found to be heteroscedastic; therefore ratio limits of agreement were used to determine bias, random error and the 95% limits of agreement. Analysis revealed the mean random error was */÷ 1.13 (95% limits of agreement being 0.78-1.00). The median error was 25% with the range being 21% to 67%. Mean and standard deviation values for each stage of the ramp test are presented in appendix J.

	Polar S710 to SRM power		
Time (mins)	**Bias**	**Random error**	**95% limits**
1	0.82	*/÷ 1.50	0.54-1.23
2	0.80	*/÷ 1.45	0.55-1.16
3	0.85	*/÷ 1.67	0.51-1.42
4	0.90	*/÷ 1.36	0.66-1.22
5	0.84	*/÷ 1.27	0.66-1.07
6	0.93	*/÷ 1.25	0.74-1.16
7	0.91	*/÷ 1.22	0.75-1.11
8	0.92	*/÷ 1.21	0.76-1.11
9	0.89	*/÷ 1.25	0.71-1.11
10	0.92	*/÷ 1.21	0.76-1.11
Overall	0.88	*/÷ 1.13	0.78-1.00

Table 5. Bias, random error and 95% limits of agreement for power recorded using the Polar S710 and SRM Powermeter during an incremental ramp test.

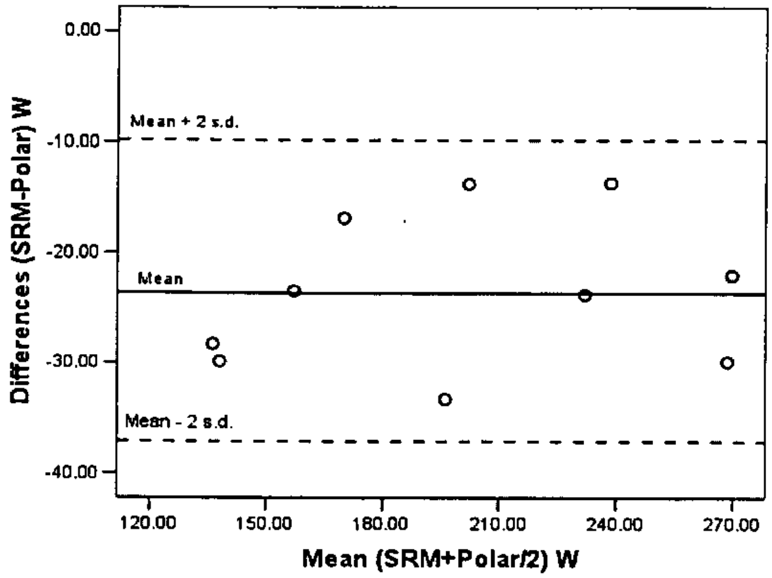

Figure 13. Bland-Altman plot of mean power output against the differences between mean power output values recorded by the SRM and Polar S710 power meters for the incremental tests

The Bland-Altman plot in figure 13 shows the heteroscedastic nature of the data during the continuous test. Ninety five percent of recorded values ranged between -9.81 W and -37.11 W. The plot suggests that the differences are greater with the highest power outputs. Reliability of the continuous tests was $r = 0.95$ and $r = 0.99$ using the S710 and SRM respectively.

Heart rate

Age-predicted HR_{max} was again 188 ± 10 beats.min^{-1}. The average peak heart rate for the continuous tests was 182 ± 8 beats.min^{-1} (range 166 to 195 beats.min^{-1}). This equated to 97 % of age-predicted HR_{max}.

Field test

Time

Mean time for the best of two test runs was 151 ± 14 s (range 135 s to 181 s). Riders spent an average of 84 ± 22 s not pedalling during their runs (range 58 s to 139 s). These non-pedalling periods accounted for 55 % of the mean run time.

Power output

Peak power output during the runs was 834 ± 129 W, and were in the range 518 to 1064 W. Peak powers were achieved within 4.5 ± 1.3 s (range 2 to 8 s). When adjusted for body mass, peak power equated to 10.7 ± 1.3 $W.kg^{-1}$. Mean power output for the runs was 75 ± 26 W (range 40 to 136 W), equating to 9% of recorded peak values when zero values were included in the analysis. When zero values were eliminated to remove bias, the mean power output for the runs increased to 185 ± 41 W (range 127 to 270 W). This subsequently equated to 22% of recorded peak values. Figure 14 shows mean power output against run time recorded at 1 s intervals during the test run. Mean and standard deviation score for field-based power output can be found in appendix K. . Field test reliability was $r = 0.95$.

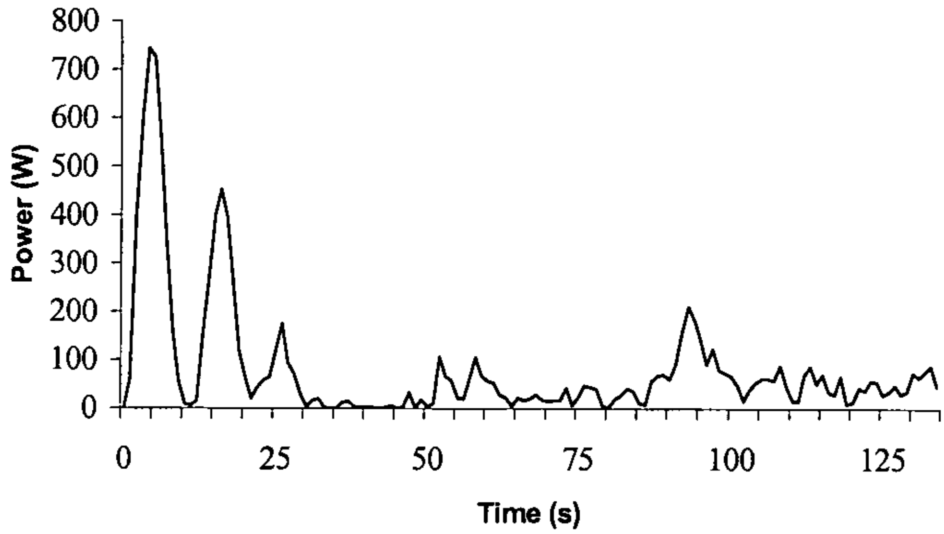

Figure 14. Mean power output calculated including zero values, recorded at 1 s intervals during the Downhill run.

Heart rate

Age predicted HR_{max} were 189 ± 5 beats.min^{-1}. Heart rate during the test run was 168 ± 5 beats.min^{-1} (range 158 to 177 beats.min^{-1}), this equated to 89% of age-predicted HR_{max}. Peak HR for the runs was 181 ± 7 beats.min^{-1} (range 169 to 197 beats.min^{-1}). Heart rates recorded at 5 s intervals during the test runs are presented in figure 15. Mean and standard deviation values for each 5 s interval can be found in appendix L.

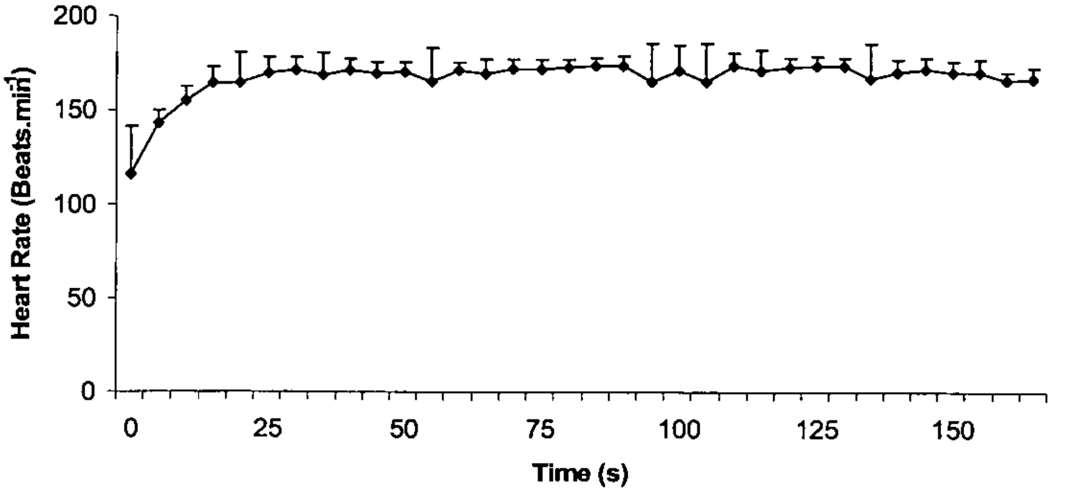

Figure 15. Mean heart rate recorded at 5 s intervals during the downhill run.

Cadence

Cadence, calculated including zero values, was 27 ± 5 revs.min^{-1} (range 18 to 35 revs.min^{-1}) for the test run. Peak cadence was 128 ± 20 revs.min^{-1} (range 99 to163 revs.min^{-1}) and was achieved at 7 ± 1.3 s (range 5 to 10 s). Again, when all zero values were eliminated from the data, mean cadence increased to 60 ± 6 revs.min^{-1}. Cadences recorded at 1 s intervals are presented in figure 16. Mean and standard deviation values for each 1 s interval can be found in appendix M.

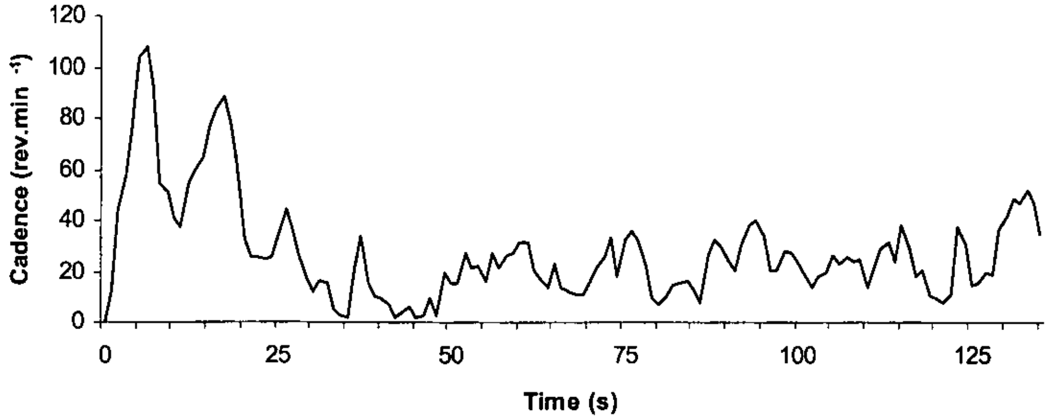

Figure 16. Mean cadence calculated including zero values, recorded at 1 s intervals during the downhill run.

Speed

Speed during the test run was 22.6 ± 2.7 km.h^{-1} (range of scores 16.6 to 26.5 km.h^{-1}). Peak speed was 38.4 ± 2.7 km.h^{-1} (range 32.8 to 43.5 km.h^{-1}). Speeds recorded for each 1 s interval during the run are presented in figure 17. Mean and standard deviation values for each 1 s interval can be found in appendix N.

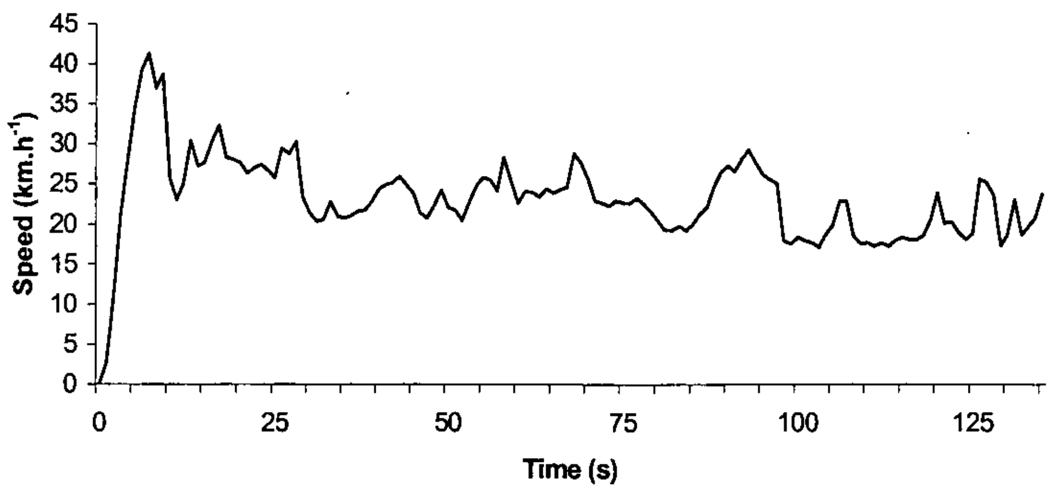

Figure 17. Mean speed recorded during the downhill run. Data sampled at 1 s intervals.

Relationships between variables

The only significant relationship identified was between average cadence and speed ($r = 0.51, p<0.01$). Mean power output was negatively related to heart rate only ($r = -0.77$, $p<0.01$). There were no significant relationships between peak power output and any of the test variables. A significant relationship existed between runtime and time spent not pedalling ($r = 0.85$, $p<0.01$). Table 6 shows that the fastest three riders spent the least time not pedalling and recorded the highest mean power values for the run. Additionally, the three slowest riders spent the most time not pedalling and recorded some to the lowest mean power values.

Subject	Run time (s)	Non-pedalling period (s)	Mean Power (W)
1	150	93	87
2	141	70	136
3	135	72	116
4	140	67	101
5	156	89	57
6	156	80	74
7	157	84	89
8	146	89	88
9	191	118	54
10	169	89	65
11	153	80	74
12	158	88	70
13	153	88	82
14	169	134	41
15	158	79	64
16	198	122	40
17	190	127	42

Table 6. Run time, non-pedalling periods and mean power output recorded during the Downhill run using the SRM Powermeter.

CHAPTER FIVE - DISCUSSION

The purpose of the present study was to investigate the energy dynamics of Downhill Mountain biking. In order to do this the best method of assessing activity of a DH nature first needed to determined. Power output is now widely accepted as one of the best indicators of exercise intensity, and the development of mobile ergometer systems have made it possible to record power output in a field environment. Subsequently, the present study investigated agreement between the SRM Powermeter and Polar S710 mobile cycle ergometer systems, initially during laboratory-based DH simulations to validate their use under high intensity intermittent conditions prior to testing under race conditions out in the field.

The major finding of the laboratory-based intermittent tests showed that there was unacceptable agreement between the Polar S710 and SRM Powermeter measuring devices when recording maximal intermittent power output. Power was underestimated by twenty three percent when using the S710 compared to values recorded using the SRM, when averaged over the duration of the test. At interval one the S710 underestimated power by fifty five percent. By interval twelve this underestimation had decreased to six percent. Both systems provided high reliability during the intermittent tests. However, the lack of agreement between the two power measuring devices was potentially the result of the large random errors.

Increases in bias were observed at intervals 3, 6 and 10 over the preceding efforts. This would indicate the influence of longer non-pedalling periods prior to these intervals (15 s, 15 s and 10 s respectively). Participants potentially recovered sufficiently during these non-pedalling periods to apply greater force to the pedals resulting in increased chain vibration and therefore the greater bias observed at these intervals. Visual observations of chain vibration would appear to support this, though further research is needed to provide scientific evidence. Additionally, small amounts of rear wheel slippage occurred between the tyre and the roller of the Kingcycle during these higher intensity efforts and may have contributed to frictional losses and therefore the increased bias reported.

The lowest random error was observed at interval 5 (36%). This was the third of three consecutive 5 s efforts with only a 5 s rest between each effort. This period of the protocol also saw a significant decrease in power output over the 3 intervals, however random errors also decreased. This decrease in power and random error suggests the onset and influence of fatigue. As participants became increasingly tired they applied less power through the pedals and to the measuring devices, resulting in a smoother less 'choppy' pedalling action. This resulted in a visible decrease in chain vibration that most likely led to the greater agreement in power output and subsequent drop in random errors that were observed between the two systems. Millet *et al.* (2003) also investigated agreement between the SRM and the S710, though their tests were conducted under continuous road riding conditions. Their results showed smaller random errors and differences of approximately 7 percent between the two systems. Road riding generally involves a more consistent smoother pedalling action than DH, therefore the smaller differences in power output reported by Millet *et al.* (2003) may have been the result of the smoother pedalling style associated with road riding and would support the finding of the present study at the lower power outputs.

Peak cadence values also stabilised between intervals three and five for SRM and S710 respectively. These values further support the supposition that fatigue influenced the decreases in power and random error observed over this period of the test. The median error was fifty one percent. Errors gradually decreased as the test progressed, again this would indicate the influence of smoother pedalling due to fatigue and decreased power output on the results.

The SRM Powermeter is widely accepted as the new 'Gold Standard' for the assessment of power output in cycling (Jones and Passfield, 1998). Using the proposed 5% error limits of Van Praagh *et al.* (1992), the results from the present study showed that the margins of error for the S710 were unacceptable when compared against the SRM using the intermittent protocol. Studies such as Jones and Passfield (1998) and Martin *et al.* (1998) assessed agreement between ergometers using continuous protocols as opposed to the intermittent protocol used in the present study. The higher errors reported in this study are likely to be the result of erratic pedalling actions caused by the stop/start nature of the intermittent test.

Friction between wheel bearings, the chain and cassette can account for some of the losses in a chain driven ergometer system (Jones and Passfield, 1998). Such losses may also have had an impact on the results of the present study. As the S710 is also a chain driven system, it too would have been affected by such losses.

Millet *et al.* (2003) also reported unacceptable errors for the S710 when comparing it to the SRM. However, contrary to the findings of the present study, Millet *et al.* (2003) found the S710 overestimated power during both field and laboratory tests when compared with the SRM. Again, these differences between the studies are likely to be the result of test methodologies, as unlike the intermittent test used in the present study, Millet *et al.* (2003) used a continuous protocol.

The present study found data were heteroscedastic. As power outputs increased the differences between the two measured values also increased. This is supported by the research of Millet *et al.* (2003).

In DH mountain biking chain slip is a major problem. The severity of courses frequently results in the chain being thrown from the chainring. To counter this problem most riders will use a chain guard and chain tensioning system such as the one shown in figure 6, chapter 3. The S710 requires a frame with conventional style chainstays for fitting. This subsequently limits the S710's compatibility with many of today's modern full suspension downhill bicycles, though that is not to say it cannot be used at all. Due to the design of the SRM it is possible to use this system incorporating a chain retaining system on non-conventional style frames in a field environment, as it bolts directly onto the bottom bracket of the bicycle.

A chain device was not used in the present study for the laboratory-based tests, though this was not a protocol oversight. The fitting of such a device would have limited the choice of gear options available to participants, as chain devices only allow the use of a single chainring. In not fitting a chain device for the laboratory-based tests, participants had the choice of using either the middle or outer chainring (36 and 42 tooth respectively) as DH cyclists will often fit a single chainring within this size range (all subjects chose a 42 tooth ring for the field tests).

Chain 'slap' (chain slapping against the chainstay) proved to be a major problem during the intermittent protocol. As participants accelerated at the start of each maximal effort, considerable chain slap was observed with the chain repeatedly hitting the chainstay sensor and bouncing in and out of the maximum recommended range of 30mm. This was most apparent during the first 3 intervals when power was highest and prior to the onset of fatigue. The S710 frequently recorded zero power values throughout the tests. This was potentially due to a combination of excessive chain vibration and moving out of range of the sensor and can partially explain the underestimation of power compared to the SRM Powermeter. During some of the shorter non-pedalling periods the S710 did not record a zero value when subjects ceased pedalling, and continued to display a power value until pedalling recommenced. Visual observations indicate that this might have been due to the slowness at which the S710 registers changes in power compared with the SRM. This was not considered to be a problem though, as it occurred on only a few occasions over all the testing. These power values were deleted from the data in order to not influence the results. Additionally, any zero values recorded during the efforts and the non-pedalling periods were eliminated from final calculations for the purpose of statistical analysis. Had a chain device been fitted for the laboratory tests, it would have potentially made little difference to the results, as they only stop the chain derailing. The chainstay sensor would still have been subjected to chain slap.

Sampling rates may also have influenced the accuracy of measurements in the present study. As one of the aims of the study was to establish the best method of recording peak power, each ergometer was set to its optimal sampling interval. A sampling rate of 1 s was selected for the SRM system. This made it relatively straightforward to pinpoint the time and magnitude of peak power, though sampling rates of 0.25 s were possible with the SRM. However, the S710 had a minimum sampling frequency of only five seconds. This may have resulted in the true peak power value not being recorded had it occurred at any time interval other than 5, 10, 15 s and so on. Consequently, it is likely that this factor contributed to the large differences observed between the two systems. Similarly, Balmer *et al.* (2004) also emphasised the need to control sampling rates when recording power.

For several participants the S710 recorded considerably lower power values than the SRM. This was most noticeable at interval seven. Actual peak power may have been significantly higher for the S710 during this 10 s effort, as it could have occurred between sampling times. Had both systems been set to sample at 5 s intervals, the differences highlighted between the two ergometers in the present study may not have been as large, as both ergometers would have potentially not recorded true peak power, suggesting that both systems provide a valid means of recording peak power during high intensity intermittent activity. However, this was not the case.

Interval seven also saw the highest random error observed during the tests. This was most likely due to participants easing up prematurely, resulting in lower values being recorded. Significant differences ($p<0.001$) were also highlighted between the two systems when cadence was averaged over the twelve intervals. This again may have resulted from unacceptable sampling frequencies with the S710 ergometer.

Mass adjusted peak power output for the present study was significantly lower than peak power values reported by Baron (2001) for elite level mountain bikers. This highlights the significant differences between the power generated by elite and non-elite trained cyclists. Peak power in the present study was comparable to that of recreationally active males (9.8 ± 1.45 W.kg^{-1}) studied by Gaiga and Docherty (1995) during a similar repeated-bouts anaerobic performance test.

Peak cadence was higher than the recommended optimal cadences suggested by Sargeant *et al.* (1981) and Patterson and Moreno (1990) using both ergometers. Sargeant *et al.* (1981) proposed that above 110 revs.min^{-1} power output would decrease. In conjunction with fatigue, this may have contributed to the significant decreases in power output observed over the duration of the intermittent test.

Though the riders that participated in the intermittent tests were from different cycling backgrounds, the peak cadence values for all subjects were comparable to those observed during field-based testing over the first few seconds. When compared to field-based values calculated including zero values, laboratory-based mean cadence was significantly higher than that observed in the field. During the field-based tests riders were required to negotiate numerous obstacles on the course. This resulted in pedalling only being possible at certain points on the course and therefore most likely led to the lower mean cadences reported in the field. When field-based cadence was calculated excluding any recorded zero values, laboratory values were still almost double those of the field values.

Though the laboratory protocol included non-pedalling phases to simulate a DH run, it could not simulate the influences of gravity and momentum acting upon riders in the field. Within the laboratory greater power and therefore higher cadences were required to accelerate the bicycle after each non-pedalling phase. Unlike this, gravity and momentum assisted in the maintenance of speed out on the course during field tests, resulting in less power and subsequently lower cadences being needed to keep the bicycle moving.

Despite the intermittent nature of the protocol, heart rates remained elevated throughout the test. Hurst and Atkins (2002) reported the only investigation into the physiological demands of DH type riding. Their preliminary study showed that average heart rate during a field-based run were 176 beats.min^{-1}. These values were higher than those reported by Wilber *et al.* (1997) and Metcalfe (2002) for XC mountain bikers; yet do not reflect the intermittent activity patterns observed during the event. The elevated heart rates demonstrated in the laboratory would again infer a continuous exercise mode contrary to the actual intermittent nature of the test.

Though the test was intermittent and maximal in nature the results indicate the need for both good aerobic and anaerobic capacity to perform well in this type of activity. At approximately 3 minutes in duration, a typical DH race will require good anaerobic capacity for the repeated short efforts. However, without sufficient aerobic ability, blood flow and therefore oxygen to the muscles will be limited resulting in fatigue.

Peak oxygen uptake values recorded during the intermittent tests equated to 88 % of those attained during the continuous tests. The high $\dot{V}O_{2peak}$ values reported during the intermittent protocol again indicate the need for good aerobic fitness as well as anaerobic ability.

The incremental protocol was conducted to determine agreement between the two systems during continuous type cycling activity. In addition, the protocol was also used to determine the aerobic capacity of the subjects and power at $\dot{V}O_{2peak}$. The main finding of the test was that significant differences ($p<0.001$) existed between the two devices. The results showed that the S710 overestimated power by twelve percent (23 ± 7 W) when compared to values obtained using the SRM system. Random error for the test was thirteen percent. The findings of Millet *et al.* (2003) support those of the present study, though Millet *et al.* (2003) found that the S710 overestimated by a smaller percentage (7 %) with smaller random errors (4.5 %). The lower random errors reported by Millet *et al.* (2003) indicate the influence of smoother pedalling associated to road riding. Random errors in the present study were also smaller during the continuous test than those observed during the intermittent test, again possible due to smoother pedalling. As with the intermittent tests, both devices provided high levels of reliability during the incremental tests. Differences were again most likely the result of the high random errors observed during the tests.

As was the case during the intermittent test, the additional errors highlighted in the continuous test during the present study compared with those demonstrated by Millet *et al.* (2003) can be attributed, in part, to frictional losses in the drive mechanism and the rear tyre/flywheel interface. The present study used a mountain bike fitted with a 26" by 1.45" slick tyre. This is considerably wider than a conventional road tyre (0.82-0.94") likely to have been used by Millet *et al.* (2003). Subsequently, this would have led to an increase in rolling resistance and therefore friction, which may have contributed to the higher overestimation of power in the present study. Winter (1991) and Woods *et al.* (1994) also stated that frictional losses can lead to overestimation of power, and both proposed a correction factor of approximately 9%.

The higher overestimation found in the present study may also be attributed to the pedalling efficiency of the sub-elite athletes tested. Inconsistencies in pedalling efficiency and pedalling patterns would result in increases in chain vibration. As the S710 uses chain speed and chain vibration the calculate power output this would potentially contribute to errors in the measurement of power. However, chain vibration during the incremental test was not as severe as during the intermittent test and therefore didn't result in the same level of zero values being recorded. This potentially caused the differences in findings between the two tests.

Bias increased slightly over the duration of the continuous test indicating that the data was heteroscedastic and influenced by increasing power outputs. This is again in agreement with the finding of Millet *et al.* (2003). In the present study random errors decreased over the duration of the tests suggesting the influence of fatigue. As the subjects became increasingly fatigued they struggled to maintain the required cadence. Additionally, subjects were using the large outer chainring by this point, resulting in the chain being put under greater tension. This combined with the slowing in cadence resulted in a visible decrease in chain vibration and potentially led to the decreases in random error as the test progressed.

The findings of the continuous tests during the present study again suggest the S710 does not fall within the 5% error limits proposed by Van Praagh *et al.* (1992). Despite similar findings, Millet *et al.* (2003) stated that the S710 *is* a valid system for measuring power output and training intensities when used by recreational cyclists. However, they also stated that it is not a valid system for scientific use or for use by elite level athletes. As Millet *et al.* (2003) used the 'professional' road version of the SRM; it is assumed that this and the S710 were fitted to a conventional road bicycle and field tests were conducted on smooth tarmac surfaces. Under these conditions it is possible that the S710 would provide an acceptable level of accuracy, as chain vibration would be relatively low due to the consistent smooth pedalling action associated with RD cycling. Chain vibration would also be affected less by the terrain. This is in agreement with the findings of the present study. As previously stated, visual observations found chain vibration to be considerably lower during the continuous ramp test, with fewer zero values being recorded, than during the intermittent tests. Millet *et al.* (2003) showed that under such field conditions, errors in mean power output were comparable to laboratory conditions. In their field tests the S710 recorded higher than the SRM by 7.4 ± 5.1 %.

Like the intermittent test, the continuous protocol found that mean and peak power values were significantly lower than those of elite level RD and XC cyclists during this type of test (Lucía *et al.*, 1998; Lee *et al.*, 2002). The same was also true for oxygen uptake. Values for these parameters were however comparable to those of non-elite cyclists and active male sports students studied by (Loftin and Warren, 1994; Baron, 2001). This again reinforces the physiological differences between elite and non-elite cyclists. Figure 7 in the results section illustrates oxygen uptake values for the intermittent and continuous protocols. Results show that $\dot{V}O_2$ uptake was greater for some subjects during the intermittent protocol than during the continuous test. This suggests that $\dot{V}O_{2peak}$ was achieved during the continuous tests rather than true $\dot{V}O_{2max}$.

Heart rates at $\dot{V}O_{2peak}$ during the incremental tests were significantly lower than those reported by Wilber *et al.* (1997) during similar tests on elite XC and RD cyclists. This is unsurprising as all of the subjects in the present study were sub-elite with the exception of one DH and one RD rider, both of whom had competed at elite level internationally. As elite riders tend to have superior cardiovascular fitness than non-elite riders it would be expected that they would attain higher HR's than sub-elite athletes in maximal stress tests such as that used in the present study. Both of the elite riders in the present study produced peak HR values (191 and 195 beats.min^{-1}) comparable to the elite XC and RD cyclists studied by Wilber *et al.* (1997).

The only published report to have used the S710 for power analysis used road cycling during testing. No studies have evaluated the systems accuracy for mountain bike riding. Results from the intermittent tests would suggest that the S710 is too susceptible to chain vibration to make it a valid means of recording power output under such conditions. As XC would also induce considerable chain movement, the S710's validity for use during continuous type field-based mountain biking activity is also questionable. The long-term effect of chain slap could also potentially damage the sensors, further reducing the systems' accuracy. However, further research would be required to provide evidence of this.

Unlike the SRM, the S710 does not allow a zero offset to be performed prior to each use in order to minimise errors. Using the SRM, this is performed by simply rotating the cranks backwards and pressing a series of button on the handlebar mounted controller. To ensure accuracy of the S710, the chain weight and the chain length must be entered into the watch/receiver unit. Unless a rider knew the default weight and length of the chain they would need to remove weigh and measure the chain periodically to minimise errors. As chains wear out they become longer through stretching, this will also affect the accuracy of the S710 ergometer, as accuracy would be greatest when using a new chain.

Few studies have assessed the anaerobic performance of all terrain cyclists. The present study aimed to provide the first reported information on the power output and cadence responses to field-based DH cycling. As a result of the laboratory tests the present study concluded that the Polar S710 did not provide a valid measure of power output during high intensity intermittent cycling activity due to the number of errors in recording. Consequently, the system was not used to monitor the dynamics of field-based DH riding. The SRM Powermeter was deemed to be the best method of determining the field-based energy dynamics of DH Mountain biking as it was not prone to the issue that affected the Polar system and provided a higher level of reliability. This was therefore used to monitor power, cadence and speed out in the field. The reliability of the field tests using the SRM Powermeter was also very high (r = 0.95) and almost identical to values derived from the laboratory-based intermittent tests further supporting the use of the SRM Powermeter for recording data during this type of high intensity intermittent cycling activity.

Time-course analysis of power outputs confirmed the previously believed intermittent nature of the activity. Unlike other cycling disciplines, the DH rider will be called upon to generate power outputs spontaneously, rather than in response to pre-ordained commands or stimuli. The magnitude and timing of these efforts will be dictated by course profile and conditions.

Mass adjusted peak power output for DH riders in the current study was lower than that reported by Baron (2001) for XC riders during laboratory-based isokinetic cycle ergometry testing. This difference is potentially due to sub-elite athletes being tested in the current study. However, the results of the current study were again comparable to those of the recreationally active males studied by Gaiga and Docherty (1995) during a laboratory-based repeated-bouts anaerobic performance test.

Given that peak power output was not significantly associated with any other test variable it appears that this component may not be an essential pre-requisite for DH performance. Indeed, subjective information from the riders suggests that the riding dynamics of this event consist of a variety of acceleration and deceleration efforts. The initial peak power generation would appear to provide a stimulus for transferring potential into kinetic energy, highlighted by the short initial 'burst' of effort. Subsequent efforts were of a lower magnitude. The purpose of these lower magnitude efforts may, again, be associated with the transfer of potential energy into kinetic forces needed to overcome occasional deceleration effects of technical terrain and braking. Overcoming such dissipative forces would appear to be the main stimulus for these subsequent efforts.

Peak power values were achieved within an average of five seconds, emphasising the anaerobic nature of these efforts. Mean power output only accounted for nine percent of the peak values recorded, suggesting that, following an initial near maximal effort, a low level of power output was sustained for most of the run.

However, when zero values were omitted from the data set, mean power increased suggesting a more moderate intensity level.

These values were lower than those recorded by Stapelfeldt *et al.* (2004) for elite male XC cyclists. However, they also found that XC racing was, to some extent, similar to DH. They highlighted that XC was also intermittent in nature, characterised by a combination of high and low power output, the magnitude and duration of which were influenced by the course terrain. The differences in mean power between the present study and that of Stapelfeldt *et al.* (2004) are most likely due to the numerous non-pedalling phases of the DH run and the uphill phases of XC. Additionally, the lower mean power outputs in DH racing may also be due to a 'freewheel' effect. At high speeds minimal force was applied to the pedals during several of the efforts following periods of non-pedalling. This was potentially due to the rider being required to catch up with the speed of the rear wheel before any force was applied through the drive system and recorded by the SRM.

Calculations for mean power and cadence were performed including zero values as well as with them omitted, as the non-pedalling periods of the run accounted for 55 % of overall runtime, and were therefore too significant to ignore. The longer a rider spent not pedalling or 'coasting', particularly in more technical sections, the more it would influence mean power output for the run. This is supported by the results presented in table 6, as they show that the three quickest riders spent the least amount of time coasting and recorded the highest mean power outputs for the DH runs. Additionally, the slowest riders produced the lowest mean power and spent more time coasting.

The variation between the peak and mean power output was particularly evident during the initial few seconds of the run, where all riders achieved their peak power output. As with events such as downhill skiing, the effort from a static start appears vital (Anderson and Montgomery, 1988). However, the current study found the time to peak power was not related to run time. This would infer that a high level of technical ability could compensate for a lack of explosive power in the initial few seconds of a DH run and help to minimise losses in speed.

Peak power output was also significantly greater than that recorded during the laboratory-based intermittent tests. This is potentially due to the suspension systems of the field bicycle compressing under acceleration and absorbing power during the start of the run. As a result greater power generation would have been required to accelerate the bicycle from the standing start. Additionally, the suspension bicycle used for field-testing was considerably heavier than the non-suspension laboratory bicycle (19.32 kg and 13.65 kg respectively). This again would have resulted in greater power output being needed to accelerate the field bicycle.

Cadence is an important determinant of power output, and can be adjusted by selecting the appropriate gear ratio at the start of the run, thereby enhancing the transfer of potential to kinetic energy. Mechanical power output in cycling is dependent upon cadence. Van Soest and Casius (2000) proposed an optimum cadence of around 130 $revs.min^{-1}$ for sprint cyclists. In the current study riders achieved peak cadences close to this recommendation. However, the average cadence that coincided with peak power was lower (96 ± 18 $revs.min^{-1}$) and closer to the recommendations of Patterson and Moreno (1990) and almost identical to the optimal cadence highlighted by Baron (2001).

Analysis of cadences revealed the average pedalling period to be less than five seconds, though the power output and cadence varied greatly. The majority of riding time was spent with the pedals static, acting more as a support platform than a dynamic performance component. This is reflected by the low mean power output for the run.

The poor relationship between cadence and power output highlighted in the present study emphasises that for DH riders the quality of force generation would be more important than simply turning the pedals. Whilst an initial near maximal effort will accrue the necessary velocity, such efforts are not characteristic of the whole run. Average cadence was significantly related to speed. This is unsurprising, as average values would share linear characteristics in terms of speed. However, cadence was not related to power output and run time. During periods when pedalling was possible, such as less technical sections or flatter areas of the run, riders appeared to produce efforts of around one third to one half of the peak power measured during the initial stages of the run. These efforts were not particularly strenuous and their use is debatable, suggesting more a low to moderate intensity 'spinning' effect. This may not act as a stimulus for the accretion of speed but would serve to prevent undue deceleration. As power and cadence did not significantly influence run times, it again indicates the importance of riding dynamics to overall performance in DH. Visual observations support this supposition, as several participants appeared to ride more 'flowingly' with seemingly minimal effort, yet still post some of the quickest run times. Though mean cadence was low, riders recorded cadences above the optimal levels recommended by Sargeant *et al.* (1981) on several occasions during their runs without any detrimental effect to performance. This is possibly the result of specific 'overspeed' training performed by DH cyclists and again suggests the greater importance of technical ability over power and cadence.

The characteristics of the DH event would appear to be unlike any other form of cycling previously reported. Downhill riding utilises an entire range of performance dynamics, from no power generation to vigorous energetic efforts. Whilst the magnitude of power output varied by rider, the tempo of pedalling appeared remarkably consistent. Indeed, analysis of time course power output curves from the SRM data revealed close similarity between the pedalling periods for all riders. This would support the contention that pedalling can only be undertaken at certain points during the run. An example of the similarities between two subjects can be seen in the SRM printouts in appendix F. However, it would appear that quicker riders may have been able to perform additional very low intensity efforts during the more technical sections of the course where other riders may have coasted or they may have left it later to stop pedalling upon approach to obstacles such as corners and jumps. These additional low magnitude efforts may have limited the deceleration effects of these technical sections and helped to maintain speed.

Difficult technical terrain will see emphasis placed on riding dynamics rather than power generation. A balance between the technical and physical dimensions of the rider's fitness would appear to be an essential component of success. Changes in course dynamics, such as wet versus dry conditions, would also ensure a variation in riding technique and subsequent energetic provision.

This dependency on the technical elements, at important parts of the run, may also explain the paradoxical relationship between heart rate and power output. A positive linear relationship between power output and heart rate is well supported. However, in the current study, heart rate showed a remarkable stability over the duration of the run when compared to the erratic nature of the power output response. As more than half of the average DH run time was spent not pedalling with the remainder being performed at a low to moderate intensity effort, it is surprising to identify heart rates consistently at almost ninety percent of maximum. Research by

Stapelfeldt *et al.* (2004) into XC racing also found mean HR to account for 91 % of maximal values and were remarkably stable despite considerable fluctuations in power output.

Such inconsistency could be explained by the dynamic and isometric muscular efforts, particularly upper body contributions, needed to overcome technical obstacles and to affect dampening of irregularities in terrain, leading to the elevated heart rates observed throughout the duration of the runs. Adrenaline levels may also have been elevated during the DH runs due to the dangerous nature of the activity. This may also have contributed to the high heart rates observed during the runs. As with the intermittent tests in the laboratory, the elevated HR's during field tests may also have been the result of responses to buffer lactate in the muscles to combat off the effects of fatigue. Unlike other variables assessed in the present study, mean field-based heart rates were comparable to those of elite cyclists studied by Padilla *et al.* (2000) during short prologue time trials.

Synthesis of results

For the present study it was hypothesised that there would be little or no difference between power values recorded by the SRM and S710 mobile power measuring devices during maximal intermittent cycling activity and therefore proposed a null hypothesis. However, the results found that the Polar S710 system was affected to a great extent by excessive chain vibration during discontinuous type cycling activity, which resulted in large random errors. Additionally, the S710's quickest sampling rate of 5 s was too indiscrete to accurately record peak power output when compared against the SRM's 1 s sampling frequency. As the SRM uses angular displacement of the crank arms to calculate power output it was less affected by chain slap or chain vibration, this resulted in far fewer zero values being recorded during the pedalling phases of the intermittent tests.

The S710 overestimated power output by up to 12 % above those recorded by the SRM Powermeter during the continuous tests. This overestimation was potentially the result of less chain vibration in response to the more consistent pedalling action associated with continuous RD type cycling and probably led to fewer errors in recording. Both systems demonstrated high reliability during the continuous tests, therefore it could be argued that the S710 does provide a level of accuracy suitable for recreational use by non-elite cyclists. As accuracy is less critical to recreational athletes they would still get an indication of how they were improving as the S710 would consistently overestimate power. For elite riders accuracy is more important and such overestimation of power could result in over training and cause a decrease in performance.

It was also hypothesised that power and cadence would be comparable between the laboratory-based DH simulations and field-based runs. However, results of the present study showed that mean power and cadence were significantly different under laboratory and field condition irrespective of whether zero values were included or excluded from the data. The differences were potentially due to greater power, and therefore cadence, being required to accelerate the bicycle following each rest period in the laboratory tests, as the riders could not rely on gravity and forward momentum to maintain speed, unlike out in the field. Results of the field tests also showed that field conditions and course profile limited pedalling opportunities to certain points on the course and subsequently lead to a reduction in mean cadence and power, contributing to the differences observed between laboratory and field values.

Limitations and directions for future research

Though the present study goes some way to identifying the field-based power output characteristics of Downhill mountain biking, it is not without limitations. One of the key limitations to this study was that field-testing was conducted on only one DH course. As discussed previously the profile of DH courses is likely to strongly influence the pedalling dynamics of DH racing and therefore the power output generated during such races. Further research may seek to confirm the power profile presented in the present study by looking at the power profiles of other DH courses. It is possible that the power characteristics of other courses may well be comparable to those in the present study given the similar duration of races and technical make-up of courses.

The present study and the work of Hurst and Atkins (2002) proposed that the elevated heart rates observed during DH runs may, in part, be the result of isometric muscular activity, particularly from upper body musculature. A further limitation of the present study is that this isometric/eccentric contribution was not investigated. Future research should consider the inclusion of electromyography (EMG) assessment of both upper body musculature in order to determine the contribution these play in DH performance and to investigate their contribution to heart rates.

A final constraint of the present study was that all subjects were required to use the same field test bicycle. Given the time and resources subjects should be allowed to use their own race bicycles to ensure maximal familiarity with the equipment. For the present study a single pivot DH suspension bicycle was used for field-testing. However, several subjects were more used to bicycles that utilised either a four-bar linkage or Virtual Pivot Point (VVP) suspension system, both of which have different ride characteristics to that of a single pivot design. For the present study the same test bicycle was used for all subjects, as only one SRM Powermeter was available for use. To fit this to every subject's bicycle would have been very time consuming.

Gaiga and Docherty (1995) highlighted the benefits of an aerobic fitness programme in reducing power decreases during repeated bouts of all out cycling activity. These finding may be of interest to the DH cyclist. As the sport demands riders perform several runs of a course during both practice and the race itself, a high aerobic capacity could potentially aid recovery between runs and subsequently help to reduce decreases in power over their runs. Further field and laboratory research might be conducted to ascertain whether top performers in DH do have higher $\dot{V}O_{2max}$ levels than lower ranked riders and whether this is associated to reductions in power drop-off during the course of a race day.

Oxygen uptake has been successfully monitored in XC cyclists in the field using the Cosmed K4 b2 (Metcalfe, 2002). However, in order to do this, the Cosmed needs to be strapped to the chest and the subject is required to wear a facemask for collection of gases. This would be a problem for assessment of $\dot{V}O_2$ during DH, as all riders are required to wear full-face helmets for safety purposes, this would not facilitate the use of the facemask. If researchers were to assess the oxygen uptake of field-based DH riding, the safety constraints and practicalities would first need to be resolved.

As a high anaerobic power output was found not to be a prerequisite to DH performance, future research might also seek to analyse the skill elements of DH riding and to investigate the contribution of upper body muscular activity to overall performance.

CHAPTER SIX – CONCLUSIONS

The results of the present study indicated that there was little agreement between power values recorded by the SRM Powermeter and Polar S710 measuring devices during maximal intermittent cycling activity. As power increased the errors between the two systems also increased. As it is generally the higher power outputs that are of most interest to the sports scientist the findings of the present study question the validity of the higher power values recorded with the S710 ergometer and therefore cast doubt on its applicability for use in monitoring DH performance. As a result of the findings of the intermittent tests the null hypothesis was rejected. Conversely, it was accepted that the SRM Powermeter system did provide a valid means of recording power output during DH type cycling activity as it provided higher reliability than the S710 and recorded lower random errors as a result being unaffected by chain slap and vibration.

The findings of the present study are supported by those of Millet *et al.* (2003) when the two systems were tested under continuous conditions. Again, as a result of the findings the hypothesis that both systems would provide a valid measure of power output was rejected. The S710 can provide an acceptable means of recording power and training intensities for recreational cyclists during continuous road cycling. However, the S710's ability to accurately record power and cadence for elite athletes and scientific studies is unacceptable. The S710's applicability to field-based continuous XC type activity is again debatable. This however, is merely conjecture and further research is needed to ascertain the systems validity during field-based XC riding.

The hypothesis that the Polar system would provide a valid measure of field-based power during DH was rejected due to the inaccuracies reported for the intermittent tests. Using the SRM as a valid means of determining the field-based dynamics of DH Mountain biking, the present study concluded that the performance energetics of DH riding can be classified as such; very high intensity efforts are used in the initial phase to accelerate the rider. These are then supplemented by continual low to moderate intensity, intermittent efforts. The contribution of these efforts to overall speed and subsequent run time remains unknown.

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APPENDICES

Appendix A

Consent form for laboratory tests.

Title of project: The validity of mobile ergometer use for the recording of power output during high intensity intermittent type cycling.

Purpose and value of study: This study aims to evaluate the validity and reliability of two mobile ergometer systems for the monitoring of power output during intermittent type cycling activities such as Downhill Mountain biking. The study also aims to investigate the physiological responses during such activity between differing cycling population.

<u>You have been invited to participate in the following postgraduate second year Sports Science project being organised by Howard Hurst.</u>

<u>The project will involve:</u>

- Recording of basic personal details and parameters including age, sex, mass, height, muscle mass, body fat, preferred cycling discipline and level of experience.
- Recording of peak power output using two mobile ergometer systems, the SRM Powermeter and the Polar S710 fitted to a standard mountain bike.
- A physically and mentally strenuous graded exercise test on a cycle ergometer with the aim of reaching subjective exhaustion or extreme effort in order to determine VO2max.
- A physically and mentally strenuous intermittent exercise test on a cycle ergometer with the aim of repeatedly generating maximal effort.
- Recording of oxygen usage using a mouthpiece linked to a personal computer.
- The measuring of heart rate using a chest strap and telemetry.

Participants are asked to refrain from any physical activity and the consumption of alcohol for 24 hours prior to the tests.

Participants may retire from the investigation at any point should they wish to do so and without prejudice.

All the data produced will be treated confidentially and individually. However the anonymous results may be used in possible future publications.

If participants wish, the results produced will be made available to them. These will include heart rate traces, power output and oxygen usage during the exercise period.

I have read and agreed to participate in the above investigation.

Name of participant (print) ....Signed .... Date ....
Name of witness (print) ....Signed .... Date ....

Appendix B

Consent form for field tests.

Title of project: The validity of mobile ergometer use for the recording of power output during high intensity intermittent type cycling.

Purpose and value of study: This study aims to evaluate the validity and reliability of two mobile ergometer systems for the monitoring of power output during intermittent type cycling activities such as Downhill Mountain biking. The study also aims to investigate the physiological responses during such activity between differing cycling population.

You have been invited to participate in the following postgraduate second year Sports Science project being organised by Howard Hurst.

The project will involve:

- Recording of basic personal details and parameters including age, sex, mass and height.
- Recording of peak power output using the SRM Powermeter mobile ergometer system fitted to a dual suspension mountain bike.
- A physically strenuous test involving maximal effort over a measured downhill course.
- The measuring of heart rate using a chest strap and telemetry.

Participants are asked to refrain from any physical activity and the consumption of alcohol for 24 hours prior to the tests.

Participants may retire from the investigation at any point should they wish to do so and without prejudice.

All the data produced will be treated confidentially and individually. However the anonymous results may be used in possible future publications.

If participants wish, the results produced will be made available to them. These will include heart rate traces, power output and cadence during the exercise period.

I have read and agreed to participate in the above investigation.

Name of participant (print) ....Signed .... Date ....

Name of witness (print) ....Signed .... Date ....

YOU WILL BE GIVEN A COPY OF THIS FORM TO KEEP, TOGETHER WITH

A COPY OF YOUR CONSENT FORM.

Appendix C

University of Central Lancashire Health 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: ______________

Appendix D

Intermittent protocol

Table shows the duration of each effort and rest period during the laboratory-based intermittent protocol.

Time (Seconds)	Duration (Seconds)	Work Rate
0 – 10	10	MAX
10 – 20	10	REST
20 – 30	10	MAX
30 – 45	15	REST
45 – 50	5	MAX
50 – 55	5	REST
55- 60	5	MAX
60 – 65	5	REST
65 – 70	5	MAX
70 – 85	15	REST
85 – 95	10	MAX
95 – 100	5	REST
100 – 110	10	MAX
110 – 115	5	REST
115 – 120	5	MAX
120 – 125	5	REST
125 – 135	10	MAX
135 – 145	10	REST
145 – 150	5	MAX
150 – 155	5	REST
155 – 160	5	MAX
160 – 165	5	REST
165 - 180	15	MAX

Appendix E

Sample of raw data for intermittent test.

Participant A - Intermittent Test

SRM Power	HR	Cadence	Time	Sample No.
60	93	7	00:00:00	1
343	116	38	00:00:01	2
512	116	50	00:00:02	3
686	123	65	00:00:03	4
700	122	75	00:00:04	5
728	126	84	00:00:05	6
705	136	91	00:00:06	7
774	126	100	00:00:07	8
802	138	108	00:00:08	9
645	139	111	00:00:09	10
65	143	45	00:00:10	11
0	144	0	00:00:11	12
0	149	0	00:00:12	13
0	150	0	00:00:13	14
0	152	0	00:00:14	15
0	155	0	00:00:15	16
0	156	0	00:00:16	17
0	152	0	00:00:17	18
0	148	0	00:00:18	19
0	148	0	00:00:19	20
349	173	48	00:00:20	21
782	173	94	00:00:21	22
783	154	103	00:00:22	23
632	152	107	00:00:23	24
576	154	110	00:00:24	25
606	152	114	00:00:25	26
679	154	118	00:00:26	27
673	153	122	00:00:27	28
650	155	125	00:00:28	29
205	156	74	00:00:29	30
0	156	0	00:00:30	31
0	156	0	00:00:31	32
0	157	0	00:00:32	33
0	155	0	00:00:33	34
0	158	0	00:00:34	35
0	157	0	00:00:35	36
0	158	0	00:00:36	37
0	158	0	00:00:37	38
0	157	0	00:00:38	39
0	158	0	00:00:39	40
0	156	0	00:00:40	41
0	157	0	00:00:41	42
0	156	0	00:00:42	43

0	154	0	00:00:43	44
0	156	0	00:00:44	45
302	158	40	00:00:45	46
754	156	89	00:00:46	47
729	158	97	00:00:47	48
672	158	103	00:00:48	49
455	157	90	00:00:49	50
0	159	0	00:00:50	51
0	158	0	00:00:51	52
0	159	0	00:00:52	53
0	158	0	00:00:53	54
0	165	0	00:00:54	55
187	158	44	00:00:55	56
708	157	103	00:00:56	57
655	162	108	00:00:57	58
551	160	112	00:00:58	59
449	162	111	00:00:59	60
0	161	0	00:01:00	61
0	161	0	00:01:01	62
0	162	0	00:01:02	63
0	161	0	00:01:03	64
0	162	0	00:01:04	65
240	163	54	00:01:05	66
714	163	108	00:01:06	67
631	164	112	00:01:07	68
582	164	116	00:01:08	69
298	164	88	00:01:09	70
0	164	0	00:01:10	71
0	163	0	00:01:11	72
0	165	0	00:01:12	73
0	163	0	00:01:13	74
0	165	0	00:01:14	75
0	165	0	00:01:15	76
0	165	0	00:01:16	77
0	167	0	00:01:17	78
0	165	0	00:01:18	79
0	166	0	00:01:19	80
0	166	0	00:01:20	81
0	167	0	00:01:21	82
0	164	0	00:01:22	83
0	165	0	00:01:23	84
0	163	0	00:01:24	85
180	164	27	00:01:25	86
677	164	84	00:01:26	87
670	164	92	00:01:27	88
619	165	97	00:01:28	89
573	164	103	00:01:29	90
568	165	107	00:01:30	91
529	165	111	00:01:31	92
544	165	114	00:01:32	93
507	166	117	00:01:33	94

382	166	103	00:01:34	95
0	167	0	00:01:35	96
0	166	0	00:01:36	97
0	168	0	00:01:37	98
0	168	0	00:01:38	99
0	168	0	00:01:39	100
218	170	58	00:01:40	101
555	169	108	00:01:41	102
494	170	111	00:01:42	103
501	165	113	00:01:43	104
481	175	116	00:01:44	105
405	170	117	00:01:45	106
388	171	117	00:01:46	107
467	171	119	00:01:47	108
450	171	121	00:01:48	109
360	172	117	00:01:49	110
18	171	38	00:01:50	111
0	168	0	00:01:51	112
0	175	0	00:01:52	113
0	172	0	00:01:53	114
0	173	0	00:01:54	115
142	172	45	00:01:55	116
514	173	108	00:01:56	117
399	173	109	00:01:57	118
412	173	111	00:01:58	119
301	173	106	00:01:59	120
0	170	29	00:02:00	121
0	175	28	00:02:01	122
0	173	0	00:02:02	123
0	172	0	00:02:03	124
0	185	0	00:02:04	125
327	185	56	00:02:05	126
544	173	103	00:02:06	127
442	172	106	00:02:07	128
391	172	107	00:02:08	129
387	172	109	00:02:09	130
401	172	110	00:02:10	131
417	172	112	00:02:11	132
343	172	113	00:02:12	133
344	172	113	00:02:13	134
341	173	114	00:02:14	135
25	173	32	00:02:15	136
0	171	0	00:02:16	137
0	174	0	00:02:17	138
0	173	0	00:02:18	139
0	173	0	00:02:19	140
0	173	0	00:02:20	141
0	172	0	00:02:21	142
0	172	0	00:02:22	143
0	173	0	00:02:23	144
13	173	13	00:02:24	145

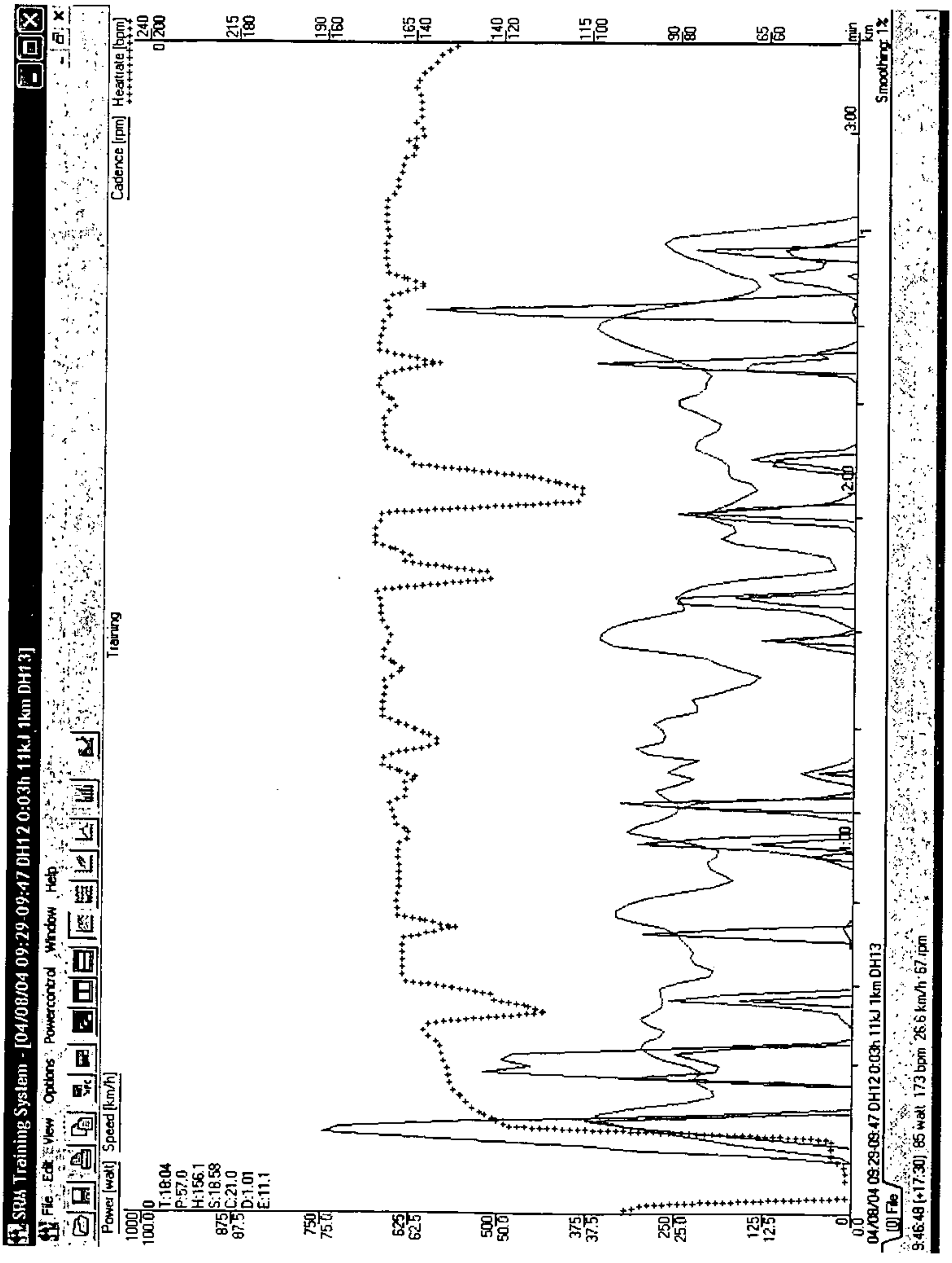
492	173	83	00:02:25	146
483	173	90	00:02:26	147
529	174	96	00:02:27	148
517	172	101	00:02:28	149
400	174	103	00:02:29	150
95	174	62	00:02:30	151
0	173	20	00:02:31	152
0	172	20	00:02:32	153
19	172	21	00:02:33	154
31	173	22	00:02:34	155
31	173	22	00:02:35	156
485	170	90	00:02:36	157
507	173	99	00:02:37	158
518	175	104	00:02:38	159
347	173	103	00:02:39	160
10	172	23	00:02:40	161
0	172	0	00:02:41	162
0	173	0	00:02:42	163
0	172	0	00:02:43	164
0	173	0	00:02:44	165
142	174	42	00:02:45	166
576	173	99	00:02:46	167
535	174	104	00:02:47	168
460	175	106	00:02:48	169
416	174	108	00:02:49	170
380	174	110	00:02:50	171
401	174	111	00:02:51	172
352	173	112	00:02:52	173
348	175	113	00:02:53	174
423	174	115	00:02:54	175
395	176	116	00:02:55	176
333	175	116	00:02:56	177
345	175	117	00:02:57	178
294	176	116	00:02:58	179
301	176	115	00:02:59	180
53	176	73	00:03:00	181

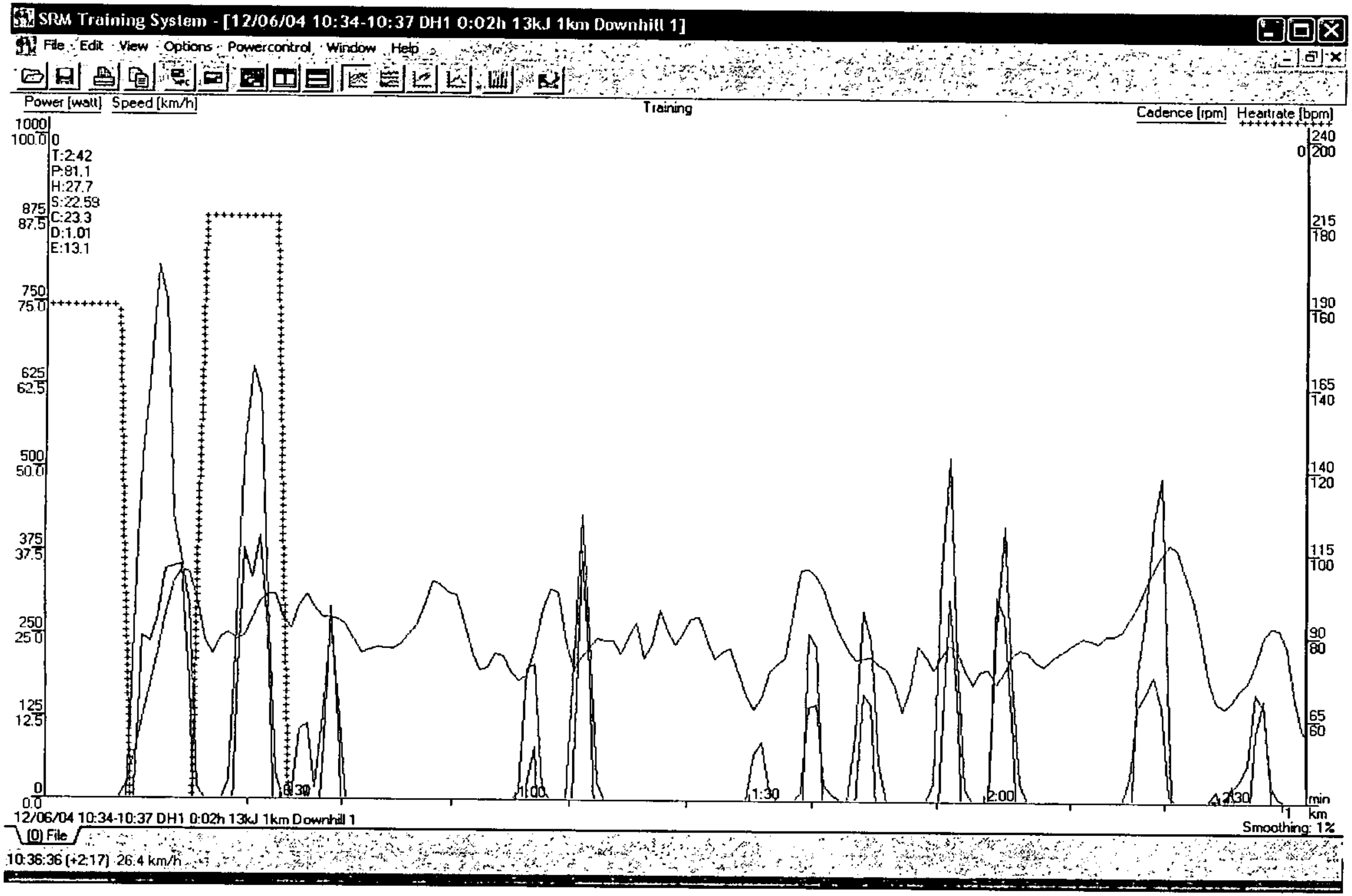
Appendix F

Sample Field data graphs for two participants.

The two traces below highlight the similarities in pedalling profile for two subjects during field-based trials.

Subjects A




SRM Training System - [12/06/04 10:34-10:37 DH1 0:02h 13kJ 1km Downhill 1]
File Edit View Options Powercontrol Window Help
Power [watt] Speed [km/h]
Training
Cadence [rpm] Heartrate [bpm]
T:2:42
P:81.1
H:27.7
S:22.59
C:23.3
D:1.01
E:13.1
0:30
1:00
1:30
2:00
2:30
min
1 km
12/06/04 10:34-10:37 DH1 0:02h 13kJ 1km Downhill 1
Smoothing: 1%
(0) File
10:36:36 (+2:17) 26.4 km/h

Appendix G

Mean and standard deviation scores for peak power output during the laboratory-based intermittent test.

SRM Powermeter

	N	Minimum	Maximum	Mean	Std. Deviation
interval1	12	460.00	995.00	710.0000	156.08331
interval2	12	486.00	919.00	718.9167	117.01861
interval3	12	412.00	851.00	652.5000	108.82054
interval4	12	426.00	740.00	622.2500	93.60082
interval5	12	457.00	714.00	578.4167	72.53270
interval6	12	408.00	709.00	589.5000	84.60550
interval7	12	395.00	604.00	491.3333	74.20896
interval8	12	339.00	578.00	442.1667	79.58510
interval9	12	346.00	660.00	465.6667	91.48505
interval10	12	361.00	653.00	472.9167	77.22277
interval11	12	361.00	667.00	462.3333	98.25415
interval12	12	366.00	611.00	468.1667	76.37210
Valid N (listwise)	12				

Polar S710

	N	Minimum	Maximum	Mean	Std. Deviation
interval1	12	301.00	626.00	460.3333	103.93996
interval2	12	350.00	736.00	587.5000	100.43134
interval3	12	239.00	580.00	453.7500	112.09908
interval4	12	354.00	759.00	484.3333	117.28933
interval5	12	358.00	723.00	510.4167	116.30013
interval6	12	253.00	628.00	439.0000	92.74403
interval7	12	143.00	554.00	413.3333	128.76782
interval8	12	298.00	546.00	392.3333	74.29956
interval9	12	252.00	572.00	422.5000	97.65291
interval10	12	303.00	570.00	401.4167	80.64113
interval11	12	229.00	570.00	409.9167	107.29184
interval12	12	293.00	589.00	447.0000	95.03588
Valid N (listwise)	12				

Appendix H

Mean and standard deviation score for HR during the intermittent test.

Time	N	Minimum	Maximum	Mean	Std. Deviation
0	12	59	96.00	79.33	11.31
5	12	69	113.00	86.75	14.05
10	12	89	120.00	103.50	9.34
15	12	114	142.00	124.17	9.55
20	12	120	151.00	134.83	9.86
25	12	119	160.00	140.08	11.48
30	12	135	164.00	145.17	8.73
35	12	138	167.00	149.00	8.93
40	12	140	170.00	152.67	8.75
45	12	142	172.00	155.17	8.83
50	12	142	172.00	155.25	8.52
55	12	145	171.00	155.25	7.59
60	12	149	171.00	156.75	7.16
65	12	151	172.00	158.42	6.64
70	12	154	175.00	160.58	6.78
75	12	156	173.00	162.42	6.27
80	12	155	176.00	162.92	7.15
85	12	156	177.00	163.58	7.40
90	12	155	176.00	162.42	7.37
95	12	155	174.00	161.58	6.87
100	12	155	177.00	162.75	7.10
105	12	156	179.00	164.33	7.64
110	12	159	179.00	166.08	6.93
115	12	159	183.00	167.17	7.85
120	12	162	184.00	168.58	7.60
125	12	161	184.00	168.75	7.90
130	12	160	184.00	168.92	8.02
135	12	162	183.00	169.50	7.38
140	12	163	184.00	170.58	7.25
145	12	163	185.00	170.67	7.15
150	12	163	182.00	170.08	6.43
155	12	162	183.00	169.92	6.82
160	12	162	184.00	169.75	6.96
165	12	163	185.00	169.92	6.86
170	12	162	184.00	169.67	6.88
175	12	162	185.00	169.92	6.91
180	12	162	186.00	170.33	7.50

Appendix I

Mean and standard deviation score for cadence during the intermittent test.

SRM Powermeter

Time (s)	Minimum	Maximum	Mean	Std. Deviation
0	65	126	93.92	20.15
5	0	141	66.67	58.63
10	0	130	10.83	37.53
15	0	144	48.17	47.20
20	61	144	119.00	24.14
25	0	152	65.75	59.90
30	0	121	10.08	34.93
35	0	129	10.75	37.24
40	0	126	26.33	40.40
45	0	130	59.42	52.35
50	0	124	39.67	45.38
55	0	122	56.58	53.02
60	0	124	39.17	43.84
65	0	135	61.42	53.14
70	0	143	11.92	41.28
75	0	110	9.17	31.75
80	0	93	18.58	33.49
85	0	125	95.25	34.49
90	0	137	80.58	52.26
95	0	132	48.00	55.69
100	0	133	97.42	47.25
105	0	124	61.17	53.13
110	0	132	45.25	50.73
115	0	121	60.50	51.44
120	0	121	37.92	47.61
125	64	129	104.33	18.82
130	0	137	70.18	58.27
135	0	29	2.64	8.74
140	0	126	34.36	49.04
145	0	127	76.36	41.09
150	0	130	28.73	44.65
155	0	124	58.27	51.39
160	0	112	30.73	43.82
165	0	127	80.64	45.82
170	0	134	102.45	36.33
175	0	136	82.75	48.83
180	0	131	55.67	53.35

Polar S710

Time (s)	Minimum	Maximum	Mean	Std. Deviation
0	0	0	0.00	0.00
5	0	66	33.08	26.33
10	54	129	95.67	24.31
15	0	106	8.83	30.60
20	0	0	0.00	0.00
25	0	115	89.58	31.03
30	85	141	125.50	18.42
35	0	0	0.00	0.00
40	0	0	0.00	0.00
45	0	0	0.00	0.00
50	0	94	62.08	37.90
55	0	84	7.00	24.25
60	0	118	85.75	42.50
65	0	97	8.08	28.00
70	0	126	88.67	43.55
75	0	130	19.42	45.71
80	0	0	0.00	0.00
85	0	0	0.00	0.00
90	0	97	50.67	38.45
95	79	131	104.42	19.83
100	0	156	43.25	64.74
105	0	133	91.75	45.46
110	0	132	98.08	47.27
115	0	130	20.25	47.43
120	0	133	70.67	54.16
125	0	113	25.58	46.55
130	0	115	58.33	52.43
135	0	130	91.42	44.35
140	0	138	40.67	60.48
145	0	90	13.92	32.62
150	0	127	53.17	49.40
155	0	127	33.08	49.95
160	0	129	49.92	53.94
165	0	117	47.83	51.00
170	0	121	48.92	52.58
175	0	125	89.92	42.84
180	0	131	94.75	46.08

Appendix J

Mean and standard deviation scores for power output during the laboratory-based continuous test.

SRM Powermeter

	N	Minimum	Maximum	Mean	Std. Deviation
increment1	12	100.00	133.00	122.0000	10.84603
increment2	12	84.00	150.00	123.0000	18.02019
increment3	12	82.00	193.00	145.3333	30.54753
increment4	12	118.00	192.00	161.5000	21.34351
increment5	12	152.00	216.00	179.5833	17.28614
increment6	12	163.00	249.00	195.2500	25.39551
increment7	12	185.00	263.00	220.0833	21.61001
increment8	12	188.00	296.00	231.6667	27.07677
increment9	12	198.00	303.00	253.5833	39.38726
increment10	12	210.00	300.00	258.6667	28.18876
Valid N (listwise)	12				

Polar S710

	N	Minimum	Maximum	Mean	Std. Deviation
increment1	12	129.00	211.00	150.2500	21.37596
increment2	12	122.00	191.00	152.8333	18.37901
increment3	12	115.00	205.00	168.7500	25.71920
increment4	12	138.00	197.00	178.3333	17.30125
increment5	12	181.00	258.00	212.8333	22.87449
increment6	12	169.00	236.00	209.0833	20.95648
increment7	12	212.00	276.00	243.8333	15.42037
increment8	12	167.00	284.00	245.3333	32.80613
increment9	12	218.00	345.00	283.4167	35.57695
increment10	12	213.00	328.00	280.6667	38.27255
Valid N (listwise)	12				

Appendix K

Mean and standard deviation scores for power output during the field-based test using the SRM Powermeter.

Time (s)	Minimum	Maximum	Mean	Std. Deviation
1	0	560	59.24	153.41
2	66	939	401.94	217.62
3	299	858	605.41	186.02
4	445	973	743.47	164.96
5	463	1016	724.12	151.41
6	207	1064	547.94	222.85
7	0	813	334.29	258.66
8	0	635	158.47	230.67
9	0	556	55.29	135.12
10	0	31	8.71	9.86
11	0	24	6.35	8.19
12	0	93	16.41	27.51
13	0	532	154.59	161.34
14	0	673	274.00	231.35
15	0	731	398.88	171.57
16	211	775	451.71	129.94
17	119	759	394.82	174.62
18	0	543	260.35	197.59
19	0	413	118.71	136.39
20	0	496	62.76	157.43
21	0	121	20.47	32.77
22	0	298	43.76	86.05
23	0	348	58.24	106.54
24	0	500	64.53	126.15
25	0	647	120.94	196.41
26	0	520	175.59	178.61
27	0	443	93.41	125.01
28	0	407	71.82	129.17
29	0	374	29.88	93.05
30	0	34	3.24	9.42
31	0	275	16.82	66.58
32	0	339	19.94	82.22
33	0	14	0.82	3.40
34	0	7	0.41	1.70
35	0	7	0.41	1.70
36	0	180	12.47	43.86
37	0	206	14.65	49.69
38	0	32	3.12	7.89
39	0	20	2.53	6.10
40	0	24	3.00	7.02
41	0	39	2.29	9.46
42	0	0	0.00	0.00
43	0	33	1.94	8.00
44	0	105	6.18	25.47

45	0	0	0.00	0.00
46	0	57	3.53	13.80
47	0	319	32.06	91.98
48	0	7	0.47	1.70
49	0	255	18.00	62.31
50	0	39	3.41	10.26
51	0	66	10.35	19.12
52	0	604	106.88	180.18
53	0	463	65.71	142.28
54	0	417	57.59	130.14
55	0	310	21.65	75.28
56	0	228	19.06	57.88
57	0	875	61.24	212.27
58	0	632	105.41	203.44
59	0	437	67.06	117.84
60	0	341	56.94	106.20
61	0	334	51.71	98.32
62	0	211	27.71	60.01
63	0	264	22.12	65.12
64	0	56	4.82	14.31
65	0	140	21.53	41.15
66	0	133	16.29	35.87
67	0	293	19.94	70.58
68	0	235	27.94	67.61
69	0	171	17.29	49.10
70	0	121	13.82	31.71
71	0	78	16.65	30.04
72	0	114	16.18	34.75
73	0	270	42.12	85.77
74	0	48	6.35	12.67
75	0	162	23.18	51.36
76	0	378	47.47	102.25
77	0	203	43.47	68.15
78	0	429	40.12	111.06
79	0	51	5.65	13.28
80	0	16	1.82	4.28
81	0	146	19.00	45.94
82	0	306	27.18	76.49
83	0	331	40.35	97.38
84	0	412	35.94	101.57
85	0	71	11.18	23.71
86	0	67	7.41	20.29
87	0	379	56.35	121.35
88	0	372	68.12	107.74
89	0	513	69.53	130.31
90	0	525	60.24	127.40
91	0	604	92.06	180.37
92	0	751	157.94	233.52
93	0	816	210.53	257.98
94	0	773	183.59	236.64
95	0	600	142.06	211.87

96	0	550	90.24	174.46
97	0	584	122.35	210.20
98	0	442	79.35	151.64
99	0	341	72.82	118.20
100	0	451	66.12	127.30
101	0	391	47.47	114.06
102	0	201	15.47	48.59
103	0	576	39.24	140.02
104	0	358	53.24	115.35
105	0	645	61.59	163.20
106	0	476	61.41	145.94
107	0	411	57.94	127.18
108	0	615	87.53	171.91
109	0	308	44.47	89.67
110	0	153	15.88	39.76
111	0	207	14.35	50.11
112	0	523	68.29	145.89
113	0	347	86.00	134.28
114	0	599	51.18	147.17
115	0	591	69.29	194.86
116	0	277	33.41	77.27
117	0	238	28.12	62.79
118	0	417	65.47	129.79
119	0	64	8.76	20.23
120	0	205	13.59	49.73
121	0	706	41.88	171.15
122	0	558	36.41	135.16
123	0	515	56.71	145.69
124	0	309	53.76	99.88
125	0	268	28.29	69.95
126	0	440	34.53	107.78
127	0	633	47.35	153.79
128	0	206	29.35	57.33
129	0	278	35.12	68.57
130	0	390	73.76	119.52
131	0	518	64.06	135.64
132	0	374	75.35	119.54
133	0	369	87.47	129.18
134	0	203	47.29	69.11

Appendix L

Mean and standard deviation score for HR during the field testing.

Time (s)	Minimum	Maximum	Mean	Std. Deviation
0	72	140	116.36	25.37
5	134	152	143.45	6.49
10	144	166	155.09	7.20
15	147	175	164.64	8.39
20	122	178	164.27	16.21
25	153	181	169.91	7.65
30	157	181	171.36	6.76
35	136	181	168.45	12.23
40	159	182	170.82	6.15
45	160	180	169.64	6.19
50	161	179	170.18	5.51
55	114	179	165.45	17.88
60	163	178	171.00	4.71
65	156	180	169.91	6.98
70	164	181	172.18	5.33
75	165	181	172.36	5.07
80	165	181	172.55	4.76
85	166	182	173.36	4.95
90	167	180	173.91	4.50
95	115	180	165.36	20.34
100	134	183	171.45	13.35
105	119	184	165.55	19.82
110	164	183	173.73	6.83
115	142	182	170.82	11.20
120	165	180	173.09	5.24
125	165	180	173.91	4.66
130	166	181	173.73	4.54
135	116	182	167.09	18.08
140	161	181	170.36	7.03
145	161	180	171.91	6.19
150	160	178	170.60	5.52
155	161	176	170.57	6.29
160	163	170	166.25	3.77
165	162	175	167.25	5.74

Appendix M

Mean and standard deviation score for cadence recorded during the field testing.

Time (s)	Minimum	Maximum	Mean	Std. Deviation
1	0	72	12.06	24.58
2	11	85	43.76	21.94
3	23	94	60.94	20.21
4	46	118	81.41	23.29
5	69	153	108.88	25.49
6	80	152	113.65	21.46
7	0	163	97.65	40.80
8	0	114	56.76	39.18
9	0	205	59.82	65.08
10	0	117	42.29	36.90
11	0	121	38.82	35.16
12	0	156	56.29	51.18
13	0	138	65.82	49.19
14	0	113	68.82	31.34
15	0	118	81.41	27.75
16	68	129	88.24	17.94
17	57	133	93.35	19.06
18	0	110	77.82	31.85
19	0	165	61.53	48.97
20	0	143	31.59	38.81
21	0	127	23.94	34.04
22	0	85	23.65	29.39
23	0	83	22.82	26.18
24	0	98	24.12	25.42
25	0	116	32.82	35.09
26	0	113	47.18	41.04
27	0	101	39.00	32.14
28	0	104	31.24	39.01
29	0	106	16.06	33.15
30	0	82	10.24	23.97
31	0	128	14.94	39.94
32	0	132	14.24	39.24
33	0	52	6.76	15.68
34	0	20	1.18	4.85
35	0	20	1.18	4.85
36	0	148	19.41	45.00
37	0	151	32.47	51.36
38	0	89	13.94	24.04
39	0	86	8.94	21.69
40	0	58	7.88	18.03
41	0	80	5.00	19.36
42	0	0	0.00	0.00
43	0	34	2.00	8.25
44	0	81	4.76	19.65
45	0	3	0.18	0.73
46	0	21	1.29	5.08

47	0	81	8.18	23.44
48	0	39	3.47	10.04
49	0	237	21.82	58.65
50	0	149	17.41	39.05
51	0	77	16.29	27.03
52	0	83	27.59	29.40
53	0	87	21.65	28.54
54	0	79	21.82	26.55
55	0	66	16.00	22.65
56	0	172	26.94	46.47
57	0	119	21.00	37.49
58	0	96	29.24	39.93
59	0	116	28.71	36.59
60	0	117	29.47	37.14
61	0	143	30.00	43.11
62	0	103	18.65	35.04
63	0	100	16.00	31.79
64	0	78	11.88	22.54
65	0	191	22.59	47.53
66	0	85	14.06	25.67
67	0	85	12.41	22.13
68	0	113	16.18	29.56
69	0	79	14.00	25.35
70	0	87	16.53	23.80
71	0	94	19.35	28.63
72	0	112	23.41	37.13
73	0	125	31.47	40.61
74	0	55	16.18	17.54
75	0	146	30.65	43.70
76	0	100	34.71	42.16
77	0	103	31.18	34.40
78	0	113	21.35	34.48
79	0	37	8.41	13.93
80	0	31	5.88	11.07
81	0	67	9.00	18.75
82	0	102	12.94	25.36
83	0	65	13.76	21.14
84	0	84	14.53	25.02
85	0	54	11.47	18.10
86	0	60	6.94	16.07
87	0	122	25.41	38.39
88	0	114	34.82	35.07
89	0	100	32.71	33.86
90	0	93	27.35	28.28
91	0	88	23.94	23.33
92	0	101	35.00	34.43
93	0	108	42.71	40.35
94	0	114	42.65	40.24
95	0	111	37.71	42.08
96	0	96	24.41	31.54
97	0	90	23.88	35.55

98	0	128	26.35	41.12
99	0	94	25.71	30.90
100	0	78	22.82	29.46
101	0	81	17.29	27.75
102	0	57	12.76	19.79
103	0	106	16.59	32.26
104	0	95	18.41	33.24
105	0	137	26.00	43.05
106	0	136	26.65	43.00
107	0	131	30.18	44.16
108	0	124	22.88	37.41
109	0	112	22.53	37.74
110	0	65	11.41	19.53
111	0	113	19.71	34.10
112	0	128	27.00	45.09
113	0	119	30.06	43.63
114	0	106	22.35	34.87
115	0	187	36.59	55.85
116	0	137	27.35	40.10
117	0	123	16.53	32.92
118	0	129	19.12	38.20
119	0	88	8.47	22.50
120	0	88	11.00	25.99
121	0	91	6.53	22.30
122	0	101	10.00	26.80
123	0	210	35.71	62.20
124	0	160	29.71	49.52
125	0	58	12.76	18.88
126	0	119	19.94	38.94
127	0	128	25.29	43.93
128	0	141	23.88	43.72
129	0	121	36.41	37.56
130	0	140	42.29	40.58
131	0	111	51.82	42.06
132	0	134	44.65	44.22
133	0	130	49.47	42.83
134	0	115	45.18	42.07
135	0	122	36.71	38.93

Appendix N

Mean and standard deviation score for speed recorded during the field testing.

Time (s)	Minimum	Maximum	Mean	Std. Deviation
1	0	11.9	2.58	3.50
2	3.2	18.1	10.74	4.52
3	12.7	23.6	17.87	3.09
4	18.2	29.4	23.75	3.67
5	23.7	33.2	29.10	3.03
6	28.3	37.3	33.34	2.93
7	32.1	38.7	35.49	1.63
8	31.1	38.2	35.04	1.79
9	22.5	37.2	30.32	4.26
10	16.6	34.3	23.87	3.81
11	16.8	26.6	21.94	2.74
12	14.9	28.7	23.57	3.76
13	14.1	28.7	23.79	3.70
14	13.6	27.3	22.69	3.27
15	15	31.1	23.04	4.32
16	16	32.8	25.42	4.62
17	17.4	33.9	27.64	3.92
18	17.3	33.1	28.51	4.00
19	21	33.1	28.55	2.88
20	24.7	31.8	28.31	2.08
21	24.4	32.6	28.21	2.88
22	19	32.4	28.84	3.50
23	23.2	31.8	29.03	2.17
24	24	30.6	28.32	1.71
25	21.4	32	27.18	2.53
26	20	32.3	26.57	2.72
27	24.2	31.3	26.65	1.82
28	19	30.2	25.45	2.60
29	20.3	29	24.66	2.45
30	18.3	27.9	22.81	3.09
31	16.8	26.2	21.72	2.81
32	15.1	26.7	21.28	2.88
33	12.8	29.6	20.81	3.79
34	15.8	34	22.00	4.56
35	13.6	37.8	21.59	6.38
36	14.1	39.1	21.95	7.38
37	14.1	37.9	22.91	7.55
38	13.5	36.2	23.27	6.30
39	12.7	34.9	24.29	6.68
40	16.7	34.8	26.06	5.96
41	14.5	33.4	26.90	6.47
42	13.6	34.3	27.14	6.58
43	15	34.2	27.81	5.83
44	16.1	32.3	26.29	4.57
45	18	32.8	25.06	4.77
46	16.6	32.7	22.51	4.88

47	16.1	34.6	22.36	5.06
48	13.9	31.6	21.38	5.65
49	8.6	32.8	22.05	5.85
50	9.9	31.7	20.16	5.16
51	14.3	32.5	20.56	4.21
52	13.2	31.3	20.21	4.77
53	13.1	29.6	22.59	4.19
54	15.8	32.5	24.93	4.83
55	16	32.8	25.86	5.04
56	16.2	32	25.48	5.03
57	17	30	24.01	4.22
58	17.5	29.6	25.37	3.31
59	14.7	31.1	24.28	3.55
60	12.7	30.2	24.23	4.17
61	13.2	31.9	25.59	4.14
62	16.8	30.6	25.38	3.36
63	19.5	28.7	24.66	2.86
64	20	31.1	26.08	3.04
65	20.7	31.6	24.18	3.01
66	18.3	30.9	24.19	3.92
67	18.5	31.9	24.50	3.75
68	15.4	30.2	23.95	4.59
69	14.1	34.3	24.40	4.37
70	19.7	31.9	25.23	3.92
71	18	31.9	24.53	3.60
72	15.1	32.8	24.32	5.05
73	16.7	29	23.73	3.97
74	16.8	30	24.29	3.92
75	13.8	32.8	24.09	4.05
76	15.4	34.2	24.01	4.33
77	17.9	37.8	24.35	6.15
78	15	40.1	23.45	7.11
79	12.3	39.2	22.30	7.95
80	10.7	37.1	21.32	8.15
81	12.3	38	20.42	7.64
82	12.8	37	20.42	6.23
83	12.3	34.9	20.93	5.50
84	11.2	32.8	20.66	6.81
85	12.1	36.1	21.26	7.02
86	12.9	35.8	22.05	7.91
87	10.6	35.7	22.76	8.54
88	12.1	36.1	22.06	7.99
89	12.3	35.6	23.15	8.39
90	8.9	36.4	23.44	9.09
91	10.4	36.1	22.75	7.63
92	12.3	35.9	23.72	7.18
93	14.1	35.1	24.77	6.35
94	1.8	34.2	24.85	7.27
95	0	35.8	22.92	7.58
96	0	34.6	21.99	7.49
97	0	30.6	21.24	6.97

98	2.6	27	19.36	6.99
99	2.9	26.7	18.87	5.74
100	2.8	27	19.56	5.83
101	3.7	30.4	18.86	6.29
102	3.9	31.3	18.41	7.25
103	0.7	29.4	18.09	7.35
104	0	29.4	20.13	6.62
105	0	28.6	20.29	6.76
106	0	28.6	19.01	7.39
107	0	30.5	18.21	8.30
108	0	32.4	19.16	9.10
109	0	32.4	19.43	9.14
110	0	33.5	19.56	9.23
111	0	32.4	19.15	9.08
112	0	31.3	19.28	8.74
113	0	29.8	18.73	9.16
114	0	31.8	19.41	9.70
115	0	36.3	19.71	9.92
116	0	40	19.35	10.40
117	0	40.8	19.48	10.76
118	0	41.5	20.02	10.46
119	6.6	41.5	22.07	9.03
120	10.4	38.9	21.96	8.02
121	8.9	35.1	21.56	7.21
122	10.8	35.5	21.72	6.69
123	3.5	38.2	20.43	7.43
124	3.5	41.5	19.38	7.72
125	4.4	41.7	20.20	7.53
126	2.8	37.6	20.80	7.75
127	1	34.3	19.53	8.77
128	0	34.8	18.48	9.27
129	0	37.6	17.82	9.74
130	0	37.6	18.33	10.11
131	0	40.8	19.45	10.48
132	0	40	21.07	10.30
133	0	38.2	21.86	9.59
134	0	39.7	22.52	8.93
135	0	36.3	22.08	10.15

Appendix O

Papers and Abstracts resulting from research.

Hurst, H.T. and Atkins, S. (2005) Agreement between Polar and SRM mobile cycle ergometer systems during laboratory based high intensity, intermittent cycling activity. *Journal of Sports Sciences*, (In Press).

Hurst, H.T. and Atkins, S. (2005) Power output of field-based Downhill Mountain biking. *Journal of Sports Sciences*, (Accepted subject to minor amendments).

Hurst, H. and Atkins, S. (2002) The physiological demands of Downhill Mountain biking as determined by heart rate monitoring. *Proceedings of the 7th Annual Congress of the European College of Sports Sciences*, Athens, Greece, July.

Agreement between Polar and SRM mobile cycle ergometer systems during laboratory based high intensity, intermittent cycling activity.

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Abstract

The purpose of this study was to assess agreement between two mobile cycle ergometer systems for recording high intensity, intermittent power output. Twelve trained male cyclists (age 31.4 ± 9.8 yrs) performed a single 3-minute intermittent cycle test consisting of 12 all out efforts, separated by periods of passive recovery ranging from 5 to 15 seconds. Power output was recorded using a Polar S710 heart rate monitor and power sensor kit and an SRM Powercrank system for each test. The SRM calculated power through torque and angular velocity, whilst the S710 used chain speed and vibration to calculate power. Significant differences (P<0.05) in power were found at 8 of the 12 efforts. A significant difference (P=0.001) was also found when power was averaged over all 12 intervals. Mean power was 556 ± 102W and 446 ± 61W for the SRM and S710 respectively. The S710 underestimated power by an average of 23% with random errors of */÷ 24% when compared to the SRM. Random errors ranged from 36% to 141% with the median being 51%. The results indicate there was little agreement between the two systems and that the Polar S710 did not provide a valid measure of power during intermittent cycling activity when compared to the SRM. Power recorded by the S710 system was influenced greatly by chain vibration and sampling rates.

Keywords: Downhill, mountain biking, power output.

Introduction

Power output is a crucial element of fitness for all cyclists and is an important indicator of performance (Winter, 1991). Advances in technology have enabled power to be recorded during field-testing using mobile ergometer systems. The most popular mobile ergometer is the SRM Powercrank system (Schoberer Rad Messetechnik, Jüllich, Germany). Strain gauges are attached to the inside of a disk situated within the inner bolt circle of the crank arm. As force is applied directly to the crank arm the gauges measure the displacement of the metal and convert this into a power value proportional to the pedal force. Several researchers have reported the reliability and accuracy of the SRM system (Jones and Passfield, 1998; Martin *et al.*, 1998; Lawton *et al.*, 1999; Balmer *et al.*, 2000; Balmer *et al.*, 2004).

One of the newest mobile ergometer systems is the Polar S710 heart rate monitor and power sensor kit (Polar, Kempele, Finland). Unlike the SRM, the S710 works by employing two sensors, one mounted on the right-hand chainstay and a second on the lower jockey wheel of the rear derailleur. Power is calculated indirectly by measuring chain tension and chain speed. Millet *et al.* (2003) investigated the validity and reliability of the S710, and the results of their research showed that the system consistently recorded power higher than the SRM system during continuous cycling activity. Indeed, most studies involving road cycling and mountain biking have employed continuous protocols (Padilla *et al.*, 2000; Baron, 2001; Bentley *et al.*, 2001; Lucía *et al.*, 2002; Impellizzeri *et al.*, 2002; Lee *et al.*, 2002).

Few studies of cycling energetics have involved intermittent protocols. In the discipline of Downhill (DH) Mountain biking such intermittent patterns are common. Despite the growing popularity of DH there is a dearth of information investigating the physiological determinants of the sport. Downhill courses generally consist of a combination of fast open fire roads, rocky paths and technical singletrack trails. Courses will also include a number of obstacles such as jumps and vertical drops. Hurst and Atkins (2002) reported the only investigation into the physiological demands of DH riding. Their preliminary study showed that heart rates during a measured run (1.7 km length, 170m vertical interval) were consistently higher than 176 beats.min^{-1}. These values were higher than those reported by Wilber *et al.* (1997) and Metcalfe (2002) for cross-country mountain bikers, yet do not reflect the intermittent activity patterns observed during the event.

The aim of the present study was to investigate agreement between two portable ergometers, the Polar S710 and SRM Powercrank systems, in determining power output during laboratory-based high intensity intermittent activity, comparable to the DH discipline.

Methods

Participants

The University of Central Lancashire ethics committee granted ethical approval and informed written consent was gained from all participants. Twelve male subjects (age 31.4 ± 9.8 years; stature 180 ± 8.1 cm; body mass 77.7 ± 8.1 kg; body fat 10.7 ± 4.2% and muscle mass 58.1 ± 4.1%) took part in the study. All participants performed cycling activity at least three times per week. As participants took part in different cycling discipline, two familiarisation sessions were conducted to ensure habituation to the intermittent protocol. All participants refrained from exercise for a period of 24 h before testing, and were asked to refrain from eating for a period of 2 h pre-test.

Instrumentation

Participants performed the test on the same test bicycle, a 48.3cm framed mountain bike with a standard diamond shape frame design. The bicycle was then mounted onto a Kingcycle ergometer (Kingcycle, High Wycombe, UK). The Kingcycle was not used for analysis purposes and was used only as a platform to mount the test rig on. Participants were allowed to use their own pedals and saddle. Height and reach were adjusted to match as closely as possible the participants' own bicycle, with a variety of stems and seat posts available for adjustment. The rear wheel was fitted with a slick tyre to ensure consistent contact with the flywheel of the Kingcycle. The test bicycle was fitted with the SRM MTB Powermeter (175mm crank length, SRM, Jüllich, Germany) incorporating four strain gauges. A Powercontrol meter was mounted on the handlebar and interfaced with the Powercrank via a wired receiver and magnet mounted on the bottom bracket shell.

The validity of the SRM has been well documented; therefore it was used as the criterion measure of power output.

The Polar S710 and power sensor kit (Polar, Kempele, Finland) was also fitted to the test rig allowing for the assessment of power via both systems during a single test. The power sensor was positioned on the right-hand chainstay while the chain speed sensor was bolted to the lower jockey wheel of the rear derailleur. A magnet was attached to upper side of the right crank arm to allow transmission of the signals. Additionally, the S710 employs a third sensor mounted to the left-hand chainstay to record speed. The three sensors were then connected to a battery on the handlebars, which in turn held the receiver.

Prior to each test a zero offset was performed to calibrate the SRM according to the manufacturers' recommendations. The Polar system was set to its optimum record interval of 5 s, whilst the SRM was set to a record interval of 1 s and data was transmitted at 500 kHz. Peak power was recorded at each interval throughout the test by both systems. Mean peak power values for each interval are presented in figure 3. As the Polar system used coded transmission and a frequency of 5 kHz, there was little risk of 'cross-talk' between the two ergometers. As an adjunct to power, peak cadence values were also recorded for each interval using the both ergometer systems.

Test Protocol

The protocol used closely simulated a UK downhill mountain bike race, which is typically 3 minutes in duration. The order and duration of each effort and rest period was determined following video analysis and observations of a downhill race. This analysis involved the video recording of five downhillers over a typical DH course. Six video cameras were set up at various key points along the course. From the video captures and observations an average profile for pedalling versus rest was created. This profile is presented in figure 1 with the recorded power values.

The course used was 1.7km in length, with a vertical interval of 174m. Starting elevation was 357 metres. Composed mainly of fast open tracks and technical single-track trails, the course was also interspersed with obstacles including two near-vertical drops of over three metres in height, cattle grids and man-made jumps. In addition, a short (<50m) section of switchbacks were also encountered.

Test Administration

Prior to the tests participants performed a 5-minute, self-paced warm up. They were then allowed to undertake dynamic flexibility activities and perform several starts in order to select an appropriate gear ratio to perform the test. Subjects then rested for 3 minutes.

Participants were given two commands. On the 'Go' command they were instructed to accelerate as hard and fast as possible and to continue pedalling until they received the 'Stop' command, at which point they were required to stop pedalling completely. This complete cessation of effort was to simulate the non-pedalling phases in DH cycling. All participants were instructed to remain in a seated position throughout the test in order to minimise upper body muscle contribution and therefore stabilise the test rig.

Statistical Analyses

Descriptive data were generated using the SPSS statistical software package (SPSS Inc., version 12.0, Chicago, Ill). Statistical differences ($P<0.05$) between power measurements were analysed using a paired students *t*-test. Differences between the power output measurements recorded with the SRM and S710 were compared using 95% ratio limits of agreement (Bland and Altman, 1986; Atkinson and Nevill, 1998). Differences between the two measures were plotted against the mean values and analysed for heteroscedasticity. Where this was evident, data were log transformed to calculate the ratio limits of agreement. For the purpose of statistical analysis any zero values recorded by either system were eliminated from final calculations so as not to skew the results.

Results

Significant differences ($P<0.05$) were found between power values recorded at all intervals with the exception of intervals 7, 8, 9 and 12 for the SRM and S710 systems. Figure 1 shows a schematic of the test protocol with the mean peak power values recorded at each of the twelve intervals for the intermittent test. A significant difference ($P<0.001$) was also found between the SRM and S710 when mean power was averaged over all twelve intervals. Mean power was 556 ± 102W and 446 ± 61W for the SRM and S710 respectively. Differences between power values increased as power output increase and therefore data were deemed to be heteroscedastic.

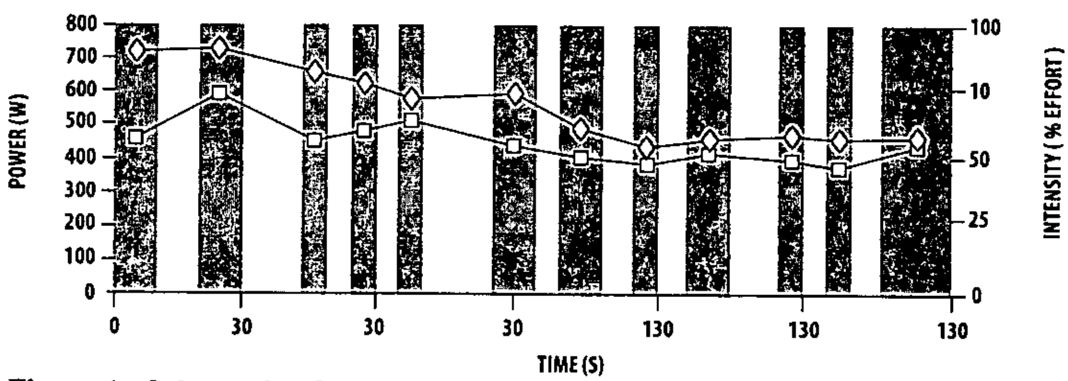

Figure 1. Schematic of test protocol. Bars represent the varying duration of each all out effort, while the gaps indicate the duration of each rest period. Mean peak power values recorded during the intermittent test using SRM (◊) and Polar S710 (□) mobile ergometers. (*) Indicate significant differences in values.

Table 1 shows the bias, random error and 95% limits of agreement (Atkinson and Nevill, 1998) for the S710 and SRM. Analysis of the ratio bias revealed that on average the S710 system underestimated peak power by 23% when compared to the SRM ergometer. The random error between the two systems was in the range of */÷ 24% (95% limits of agreement being 0.99-1.53). The Bland-Altman plot presented in figure 2 shows that 95% of power values recorded ranging between –18.16 W and 238.71 W. The results also highlighted increases in bias at intervals 3, 6 and 10 (bias =1.46, 1.36 and 1.18 respectively) over the previous interval. The median random error was 51%, while the minimum and maximum error values were 36% and 141% respectively.

	Polar S710 to SRM power		
Interval	Bias	Random error	95% limits
1	1.55	*/÷ 1.88	0.83-2.91
2	1.22	*/÷ 1.67	0.73-2.04
3	1.46	*/÷ 1.91	0.76-2.79
4	1.30	*/÷ 1.51	0.86-1.96
5	1.15	*/÷ 1.36	0.85-1.56
6	1.36	*/÷ 1.57	0.87-2.14
7	1.26	*/÷ 2.41	0.52-3.04
8	1.13	*/÷ 1.51	0.75-1.71
9	1.12	*/÷ 1.50	0.75-1.68
10	1.18	*/÷ 1.40	0.84-1.65
11	1.13	*/÷ 1.40	0.81-1.58
12	1.06	*/÷ 1.50	0.71-1.59
Overall	1.23	*/÷ 1.24	0.99-1.53

Table 1. Bias, random error and 95% ratio limits of agreement for Polar S710 and SRM Powercrank power recorded during a 3-minute intermittent test using ratio values.

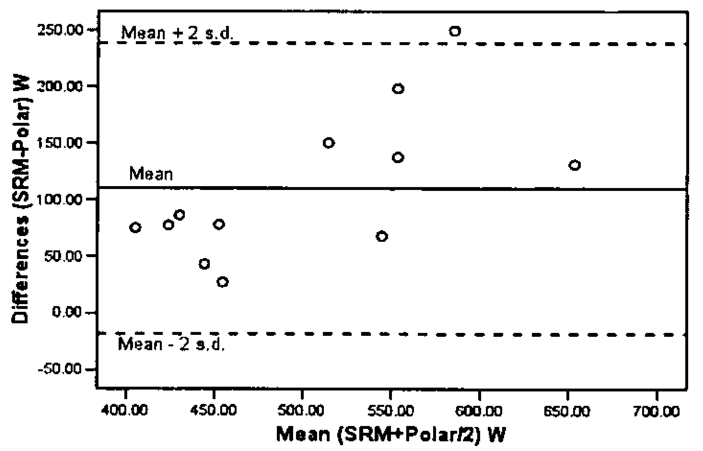

Figure 2. Bland-Altman plot of mean peak power output against the differences between power output values recorded by the SRM and Polar S710 ergometers.

Significant differences ($P<0.001$) were found for cadence values recorded by the SRM and S710 (136 ± 15 rev.min^{-1} and 129 ± 15 rev.min^{-1} respectively) when averaged over the twelve intervals.

Discussion

The aim of this study was to assess agreement between two portable cycle ergometer systems for recording intermittent power output. The protocol used in the present study could be used to monitor fitness and possibly help predict performance in intermittent activity such as DH Mountain biking. It is therefore important that power is accurately recorded during this type of testing.

The major finding of the present study showed that there was no association between the S710 and SRM ergometers when recording maximal intermittent power. Power was underestimated by twenty three percent when using the S710 compared to values recorded using the SRM when averaged over the entire test. At interval one the S710 underestimated power by fifty five percent, by interval twelve this had decreased to a six percent underestimation.

Increases in bias were observed at intervals 3, 6 and 10 over the previous efforts. This indicates the influence of longer rest periods (15 s, 15 s and 10 s respectively) prior to these intervals. Participants potentially recovered sufficiently during these periods to apply greater force to the pedals resulting in greater chain vibration and therefore the greater bias observed at these intervals. Additionally, rear wheel slippage between the tyre and roller of the Kingcycle during these higher intensity efforts may also have contributed to frictional losses and therefore the increased bias reported.

The lowest random error was observed at interval 5 (36%). This was the third of three consecutive 5 s efforts with only a 5 s rest between each effort. This period of the protocol saw the greatest decrease in power over any 3 intervals, however random errors also decreased. This decrease in difference and random error suggests the influence of fatigue. As participants became increasingly tired they applied less power to the two ergometers, resulting in a smoother less 'choppy' pedalling action. This caused a visible decrease in chain vibration that most likely led to the greater agreement in power and subsequent drop in random errors that were observed between the two systems. Millet *et al.* (2003) investigated agreement between the SRM and the S710 under continuous road riding condition. Their results showed smaller random errors (*/÷ 1.06%) and differences of approximately 7 percent between the two systems. Road riding involves a more consistent smother pedalling action than downhilling therefore the smaller differences in power output found by Millet *et al.* (2003) may have been the result of the smoother pedalling action associated with road riding and would support the finding of the present study for the lower power outputs.

Additionally, mean peak cadence values also decreased between intervals three and five for both systems (119 ± 14.35 rev.min^{-1} to 107 ± 18.14 rev.min^{-1} and 109 ± 12.92 rev.min^{-1} to 88.33 ± 16.10 rev.min^{-1} for SRM and S710 respectively). These values further support to the idea that fatigue influenced the decreases in power and random error observed over this period of the test. The median error was fifty one percent. Errors of this magnitude occurred more frequently as the test progressed. This again, would indicate the result of smoother pedalling as fatigue took effect and power output decreased.

Research by Van Praagh *et al.* (1992) suggests that all cycle ergometers should be within a 5% margin of error to provide a valid and reliable measure of power. Jones and Passfield (1998) and Martin *et al.* (1998) compared the SRM against the chain driven Monark ergometer system. Both studies reported margins of error within this accepted 5% limit (~1% and 2.36% respectively). However, unlike the aforementioned studies, results from the present study show that margins of error were unacceptable when using the intermittent protocol. Studies such as Jones and Passfield (1998) and Martin *et al.* (1998) assessed agreement using continuous protocols unlike the intermittent protocol used in our study. Differences in errors between these studies and the present study are likely to be the result of erratic pedalling actions caused by the stop start nature of the intermittent protocol. Differences between ergometers reported by Jones and Passfield (1998) and Martin *et al.* (1998) were attributed to losses within a drive chain system. As the S710 is also a chain driven system, it too would have been affected by losses, potentially to a greater extent due to the intermittent protocol used.

The present study found data to be heteroscedastic. That is that as power values got larger, so did the differences between those values. This is supported by the research of Millet *et al.* (2003). Similarly to the present study, Millet *et al.* (2003) reported unacceptable errors when comparing the S710 to the SRM. However, contrary to the finding of the present study, Millet *et al.* (2003) found the S710 overestimated power during both field and laboratory tests (7.4 ± 5.1% and 6.8 ± 7.9% respectively) when compared to the SRM. Again, these differences between studies are likely the result of losses in the drive chain and test methodologies, as Millet *et al.* (2003) used a continuous protocol. Downhilling is a high intensity activity; therefore it is the higher powers that are of most interest to the sports scientist. The results of the present study highlighted that higher power values record with the S710 ergometer were not reliable.

Results showed that Chainslap (chain slapping against the chainstay) proved to be a major problem during the intermittent protocol. As participants accelerated at the start of each all-out effort, considerable chainslap was observed with the chain repeatedly hitting the chainstay sensor and bouncing in and out of range of the sensor. This was most apparent during the first 3 intervals when power was highest and before the onset of fatigue.

During field-based DH cycling this chainslap and chain slip is a major problem and would potentially lead to further inaccuracy when measuring power in the field. The severity of courses frequently results in the chain being thrown from the chainring. To counter this problem and to reduce chain vibration most riders will use a chain guard and chain tensioning system. The S710 requires a frame with a standard style chainstay, such as the type used in the present study. However, many modern full suspension DH mountain bikes are unconventional in design, therefore the compatibility of the S710 with DH bicycles may be limited. Frame design is not an issue with the SRM ergometer as it bolts directly onto the bottom bracket of the bicycle. A chain device was not used in the present study though this was not a protocol oversight. The fitting of such a device would have limited the choice of gear options available to participants, as chain devices only allow the use of a single chainring. In not fitting a chain device for the laboratory-based tests, participants had the choice of using either the middle or outer chainring as DH cyclists will often fit a single chainring of either of these sizes i.e. 38 or 42 tooth.

The S710 frequently record zero power values throughout the tests. This was potentially the result of chain vibration and could partially explain the underestimation of power. During some of the shorter rest periods the S710 did not record a zero value and continued to display a power value until just before pedalling recommenced. These power values were deleted from the data in order to not influence the results. This was not considered to be a problem though as it occurred on only a few occasions throughout testing.

Friction between wheel bearings and the chain and cassette account for some of the losses in a chain driven ergometer system. Further losses are associated with the rolling resistance of tyres (Martin *et al.*, 1998). Such losses may also have had an impact on results in the present study, as the S710 is also a chain driven system. Though 'slick' in profile, the rear tyre used in the present study was wider than an average road tyre, potentially leading to increased losses. As mentioned previously, wheel slippage following the longer rest periods may also have lead to increases losses during these intervals, as a restraining strap was not used during the present study.

Sampling rates influenced the accuracy of measurements in the present study. As the study aimed to establish the best method of recording peak power, each ergometer was set to its optimal sampling interval. A sampling interval of 1 s was selected for the SRM system. This made it relatively easy to pinpoint the time and magnitude of peak power. Sampling rates of 0.25 s were possible with the SRM though would have yielded little difference to 1 s sampling. The S710 has a minimum sampling frequency of 5 s and this may have resulted in the true peak power value not being recorded with this system if it occurred at any time interval other than 5, 10, 15 s and so on. Consequently, it is likely that this factor contributed to the large differences observed between the two systems.

For several participants the S710 recorded significantly lower peak power values than the SRM. This was most noticeable at interval seven. Actual peak power may have been significantly higher for the S710 during this 10 s effort, as it could have occurred between sampling times, for example at the 7^{th} second. Had both systems been set to sample at 5 s intervals, the differences highlighted between the two ergometers in the present study may not have been as large, suggesting greater agreement than there actually was. Interval 7 also saw the highest random error observed during the tests (141%). This is most likely due to participants easing up prematurely, resulting in lower values being recorded.

Significant differences ($P<0.001$) were also highlighted between the two systems when cadence was averaged over the twelve intervals. This again may have resulted from unacceptable sampling frequencies with the S710 ergometer. The need to control sampling rates when recording power has also been emphasised by Balmer *et al.* (2004).

Conclusion

The results of the present study indicate that there was an unacceptable level of agreement between power output values recorded by the Polar S710 and SRM mobile ergometers during maximal intermittent cycling activity. The findings indicate that the S710 system is potentially affected too much by excessive chain vibration during this type of testing and that sampling rates are too indiscrete to accurately record peak power output. Future research might seek to examine the responses to DH riding in a field setting using the SRM as a valid means of measuring power output.

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Power output of field-based Downhill Mountain biking.

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Abstract

The purpose of this study was to assess the power output of field-based Downhill Mountain biking (DH). Seventeen trained national level, male downhill cyclists (age 27.1 ± 5.1 yrs) performed two timed runs of a measured downhill course. An SRM powermeter was used to simultaneously record power, cadence and speed. Values were sampled at 1 s intervals. Heart rates were recorded at 5 s intervals using a Polar S710 heart rate monitor. Peak and mean power output were 834 ± 129 W, and 75 ± 26 W respectively. Mean power accounted for only 9% of peak values. Paradoxically, mean heart rate was 168 ± 9 beats.min^{-1} (89% of age-predicted maximum heart rate). Mean cadence (27 ± 5 revs.min^{-1}) was significantly related to speed (r = 0.51; $p<0.01$). Analysis revealed an average of 38 pedal actions per run, with average pedalling periods of 5 s. Power and cadence were not significantly related to run time or any other variable. Results support the intermittent nature of DH Mountain biking. The poor relationships between power and cadence to run time suggest they are not essential pre-requisites to DH performance and indicate the importance of riding dynamics to overall performance.

Keywords: Mountain biking, power, cadence, heart rate.

Introduction

Mountain biking has become increasingly more popular as both a sport and leisure activity over the past decade (Baron, 2001). The sport encompasses several disciplines with cross-country (XC) and downhilling (DH) being the most popular. Cross-country gained acceptance as an Olympic event in 1996, generating further interest and increasing the high-profile status of the sport. Though not an Olympic sport, DH has a similar profile, and is rapidly becoming one of the most popular of the mountain bike disciplines with its own World cup competition and numerous other global series. At a recent World cup event, held at Fort William in Scotland, over 20000 spectators viewed the downhill event, emphasising the sports popularity.

Downhill Mountain biking involves riders competing over a measured course against the clock. Competitors usually perform two timed runs, with their fastest run counting towards the final result. The majority of UK DH races are typically between 2 and 4 minutes in duration, and require competitors to ride over a variety of terrain. These range from fast open fire roads, rock strewn paths and technically demanding single-track trails. Courses will also include a number of obstacles such as jumps and vertical drops. The energetic profile observed is one of intermittent physical activity (Hurst and Atkins, 2002).

Despite such popularity there is a dearth of information assessing the energetics of mountain biking (Atkinson *et al.*, 2003). In the only reported study pertaining to the DH event, Hurst and Atkins (2002) reported that heart rates (HR) were consistently in excess of 176 beats.min^{-1}. However, the results did not recognise the intermittent nature of the DH (Hurst and Atkins, 2002). No other studies have looked at the energetic demands of DH riding. Mean HR values reported by Hurst and Atkins (2002) were higher than those reported by Impellizzeri *et al.* (2002) and Stapelfeldt *et al.* (2004) who established that average HR during XC racing were 171 $\pm$ 6 beats.min^{-1} (90 % of field HR_{max}.) and 177 $\pm$ 7 beats.min^{-1} (91 % of Laboratory HR_{max}.). Values were however comparable to those reported by Padilla *et al.* (2000) for professional road cyclists during field-based short duration prologue time trials (177 $\pm$ 5 beats.min^{-1}) equating to 89 $\pm$ 3 % of HR_{max}.

The most commonly used method of determining field-based exercise intensity has been heart rate monitoring (Terbizan *et al.*, 2002). Hurst and Atkins (2002) emphasised a paradox for the assessment of DH performance. Whilst heart rates were almost stable throughout the performance, the actual observed pattern of activity was intermittent. Stapelfeldt *et al.* (2004) also observed a similar pattern of intermittent activity by during XC racing and highlighted a disparity between HR and power output. Despite considerable fluctuations in power output, HR remained relatively constant at 177 $\pm$ 6 beats.min^{-1}. This type of cycling activity would advocate the use of alternative assessments of energy expenditure to accommodate this intermittent pattern.

Power output, both aerobic and anaerobic, is an important indicator of performance and is widely acknowledged as a more direct measurement of exercise intensity (Jeukendrup and Van-Diemen, 1998). The assessment of power output in the field setting has been difficult in the past, though this is now possible using mobile ergometer systems. However, limited information exists using these systems in field-based trials. Similarly, information on the use of these systems for measuring intermittent physical activities remains rare. Given the dearth of information available, the current study was designed to provide the first reported details of power output during field-based DH riding.

Materials and methods

Participants

Seventeen male participants (age 27.1 $\pm$ 5.1 years; stature 179 $\pm$ 1 cm; body mass 77.6 $\pm$ 6.9 kg) gave informed written consent to take part in the study. All subjects were national level DH mountain bikers, and competed on a regular basis. Subjects trained using a combination of DH and XC modalities, to a ratio of 3:1. Prior to testing all subjects refrained from exercise for a period of 24 h, and were asked to refrain from eating for 2 h pre-test.

The Course

All tests took place on the same course. The chosen course is used as a competitive venue on the UK race circuit. The course was 1.7 km in length, with an altitude drop of 174 m. Starting elevation was 357 metres. This descent profile is outlined in figure 1. The course primarily consisted of technically demanding single-track trails and open fire tracks, interspersed with two near vertical 'drop offs' of over three metres in height. In addition, a short (<50 m) section of switchbacks was also encountered.

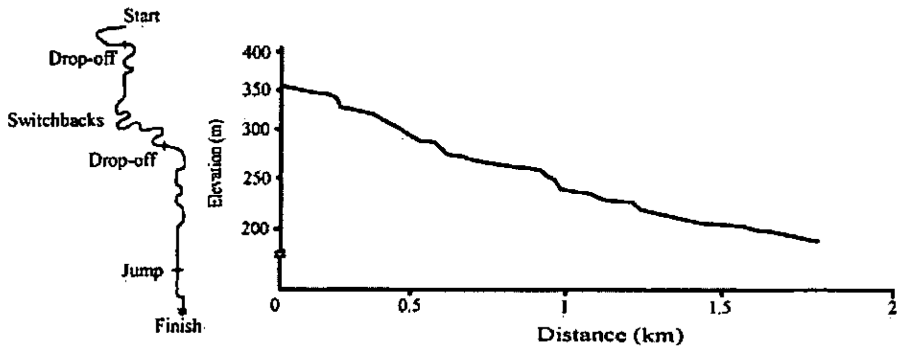

Figure 1. Course and descent profile of the track used for field-testing.

Equipment

Participants wore a protective 'armoured' jacket consisting of torso, spine and full length arm padding and a kidney belt, along with padded trousers. Additionally, shin pads were also used. All riders wore full-face protective helmets and gloves. A 43.2 cm frame, Sintesi Bazooka full suspension downhill bike was used (Sintesi, Italy). The bike had suspension dampening set at 16.8 cm of travel for the front and rear shock units. A selection of seat posts and stems were available to ensure best fit for riders. Of the 17 riders, 14 chose to use 'clip-in' pedals similar in design to those used by road cyclists. Only three riders chose to use flat 'BMX' style pedals, with no restraint system.

Power Output

The Schoberer Rad Messetechnik (SRM) Training System measures power output directly at the crank arm. Precision strain gauges are attached to the inside of a deformable disk situated within the inner bolt circle of the crank arm. As force is applied to the cranks the gauges convert this into a power value. The product of torque and cadence is assessed with every pedal revolution. This signal is then transmitted to a handlebar mounted power controller. Several studies have emphasised the validity of this system in laboratory situations (Lawton *et al.*, 1999; Balmer *et al.*, 2000a, 2000b; Davison *et al.*, 2000; Balmer *et al.*, 2004). Gardner *et al.* (2004) established that the SRM also provided a valid measure during field conditions over a range of power when compared to dynamic calibration. Power output in the current study was measured using a 4 strain gauge SRM Powermeter (MTB model, SRM, Jüllich, Germany). This has been shown to be a reliable and accurate means of recording power when compared with 20 strain gauge scientific cranks (Jones and Passfield, 1998). For this test, the SRM system was set to record at 1 s intervals. Times for the runs were also recorded using this device. Prior to each test run, the zero offset of the powermeter was re-entered into the powercontrol unit in accordance with the manufacturer's guidelines.

The SRM Powercranks were attached to the test bike through a downhill specific chain retention device. Chain 'slip' is a common concern to downhill cyclists, and these devices provide a measure of security to prevent this occurrence.

Power output was recorded as the average and peak power values measured during the test run. As an adjunct to power measurement the SRM system also allowed the recording of cadence and speed. Again, values are expressed as the average and peak values measured during the test run.

Heart Rate

Heart rate was recorded using a short-range telemetry system (S710, Polar, Kempele, Finland). Chest straps were placed inferiorly to the xiphosternal joint. The heart rate monitor was set to it shortest sampling rate of 5 s intervals. Age predicted heart rate was determined using the equation of Tanaka *et al.* (2001).

Test Administration

Subjects completed a two stage warm up consisting of dynamic flexibility activities and large muscle group activities aimed at elevating the heart rate. In addition, riders undertook a pre-test familiarisation session involving a 'walk down' of the route and practice runs. Riders then performed two timed runs separated by a 2 h rest period. Each rider's quickest run was used for analysis. The SRM system was set to record from five seconds prior to the start of the test run. On the command "3, 2, 1, GO" subjects left the designated start gate. Following completion of the test run, recording was stopped within 20 seconds. All tests occurred under dry course conditions.

Statistical Analysis

Mean and standard deviation scores were calculated for average and peak power output, cadence, speed and heart rate. Time to peak power was also recorded. The range of scores measured was also identified. Descriptive data were generated using the SPSS statistical software package (SPSS Inc., version 12.0, Chicago, Ill). Relationships between test variables were identified using the Pearson's Product Moment correlation coefficient. Significance levels were set at $p<0.05$. All subjects recorded zero values for both power and cadence during non-pedalling phases of the runs. Data for mean power and cadence are presented with the zero values both included and excluded, as the non-pedalling phases were an important contribution to the runs.

Results

Mean values ± standard deviations are presented in Table 1 for all field-based variables. On average subjects spent 84 ± 22 s of their run time not pedalling or 'coasting' (range 58 s to 139 s). This accounted for 55 % of the mean run time.

Variables	Mean ± S.D.	Range
Mean run time (s)	151 ± 14	135 - 181
W_{peak} (W)	834 ± 129	518 - 1064
W_{mean} (W)	75 ± 26	40 - 136
Time to peak power (s)	4.5 ± 1.3	2 - 8
HR_{mean} (beats.min^{-1})	168 ± 9	158 - 177
HR_{peak} (beats.min^{-1})	181 ± 7	169 - 197
Mean cadence (revs.min^{-1})	27 ± 5	18 - 35
Peak cadence (revs.min^{-1})	128 ± 20	99 - 163
Average speed (km.h^{-1})	22.6 ± 2.7	16.6 - 26.6
Peak speed (km.h^{-1})	38.4 ± 2.7	32.8 – 43.5

Table 1. Responses to field-based Downhill Mountain Biking. Values presented in table 1 are mean ± S.D. when all zero values from non-pedalling phases were included in the analysis.

Power Output

Mean power output for the runs was 75 ± 26 W (range 40 to 136 W), equating to 9% of the recorded peak values when zero values were included in the analysis. When zero values were removed from the analysis, mean power output for the runs increased to 185 ± 41 W (range 127 to 270 W), equating to 22% of recorded peak values. Figure 2 shows the mean power values recorded at 1 s intervals during the downhill runs. The graph would suggest a lower mean peak power value of approximately 760 W than the actual peak value recorded; however, this is due to riders achieving peak power at different time points during the run. Therefore power over the first few seconds was calculated included both peak values for some subjects and sub-peak for others at each 1 s time interval.

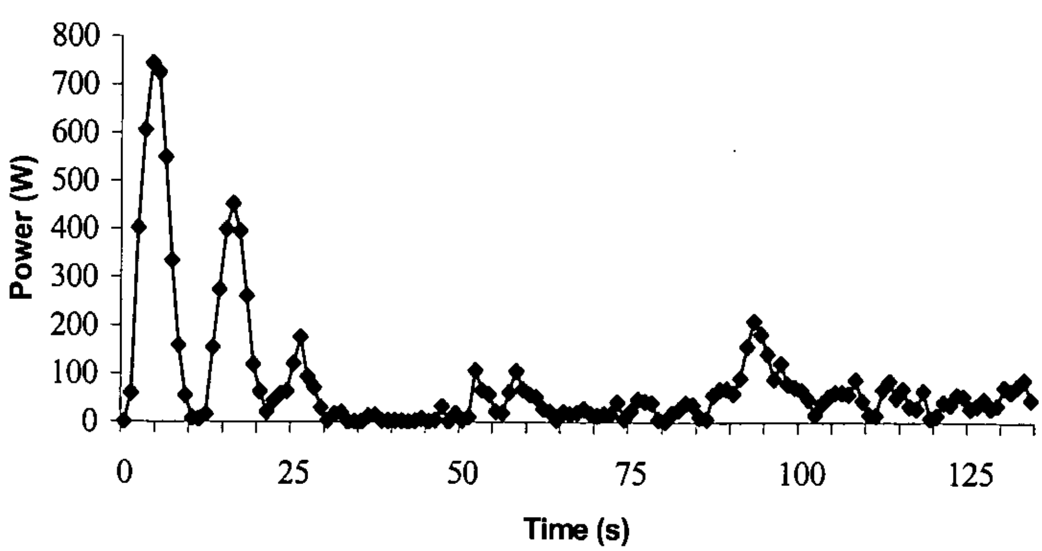

Figure 2. Mean power values recorded at 1 s intervals during the Downhill runs. The average peak power for all subjects was higher than peak values presented in the graph. This is due to riders achieving peak power at different time point.

Heart Rate

Age predicted HR_{max} were 189 ± 5 beats.min^{-1}. Mean HR during the test runs equated to 89% of age-predicted HR_{max}. Mean HR's recorded at 5 s intervals during the test run are presented in figure 3.

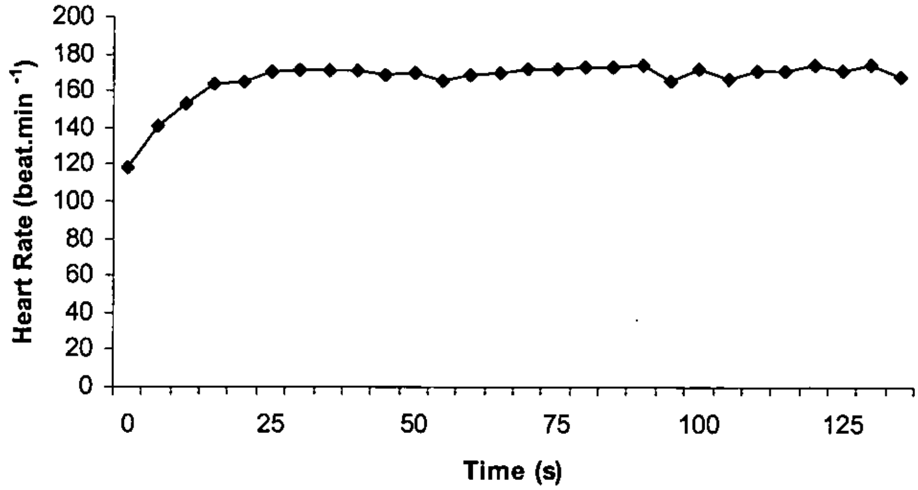

Figure 3. Mean heart rate recorded at 5 s intervals during the downhill run.

Cadence

Mean run cadence, calculated including zero values, was 27 ± 5 revs.min^{-1} (range 18 to 35 revs.min˙1). Mean peak cadence was 128 ± 20 revs.min^{-1} (range 99 to163 revs.min^{-1}) and was achieved at 7 ± 1.3 s (range 5 to 10 s). Figure 4 presents mean cadences recorded at 1 s intervals. As with peak power, peak cadence occurred at different time points for each subject, therefore the mean peak value in figure 4 appear lower than the actual mean peak cadence. Again, when all zero values were eliminated from the data, mean cadence increased to 60 ± 6 revs.min^{-1}.

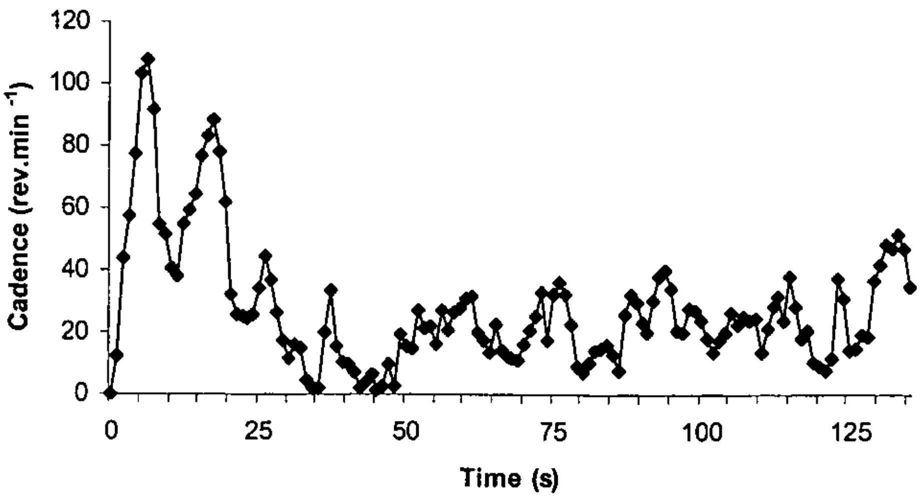

Figure 4. Mean cadence recorded at 1 s intervals during the downhill run.

Relationships between variables

The only significant relationship identified was between average cadence and speed ($r = 0.51$; $p<0.01$). Mean power output was negatively related to heart rate only ($r = -0.77$; $p<0.01$). Mean and peak cadence was moderately related to run time ($r = 0.22$ and 0.42 respectively), though the relationships were not significant. There were no significant relationships between peak power output and any of the test variables.

Discussion

Few studies have assessed the anaerobic performance of all terrain cyclists. The current study provides the first reported information on the power output, cadence and heart rate response to downhill mountain bike riding. Time-course analysis of power outputs confirmed the previously believed intermittent nature of the activity. Unlike other cycling disciplines, the DH rider will be called upon to generate power outputs spontaneously, rather than in response to predetermined commands or stimuli. The magnitude and timing of these efforts will be dictated by course profile and conditions.

Mass adjusted peak power output for DH riders in the current study was 10.7 ± 1.3 W.kg^{-1}. Baron (2001) reported a higher value of 14.9 ± 1.1 W.kg^{-1} for XC riders respectively during laboratory-based isokinetic cycle ergometry. This difference is potentially due to sub-elite athletes being tested in the current study. Additionally, as the test runs started on a declining slope, less power would have been need to accelerate the bicycle from standing start. The results of the current study were however comparable to those of recreationally active males (9.8 ± 1.5 W.kg^{-1}) studied by Gaiga and Docherty (1995) during a laboratory-based repeated-bouts anaerobic performance test.

Given that peak power output was not significantly associated with any other test variable it appears that this component may not be an essential pre-requisite for DH performance. Indeed, subjective information from the riders suggested that the riding dynamics of this event consist of a variety of acceleration and deceleration efforts. The initial peak power generation would appear to provide a stimulus for transferring potential into kinetic energy, highlighted by the short initial 'burst' of effort. Subsequent efforts were of a lower magnitude. The purpose of these lower magnitude efforts may, again, be associated with transfer of potential energy into kinetic forces needed to overcome occasional deceleration effects of technical terrain and braking. Overcoming such dissipative forces would appear to be the main stimulus for these subsequent efforts.

Peak power values were achieved within an average of five seconds, emphasising the anaerobic nature of these efforts. Mean power output (calculated including zero values) only accounted for nine percent of the mean peak power, suggesting that, following an initial near maximal effort, a low level of power output was sustained for most of the run. However, when zero values were omitted from the data set, mean power rose to 185 ± 41 W, suggesting a more moderate intensity level. These values are lower than those recorded by Stapelfeldt *et al.* (2004) for XC racing. Their research reported mean power values of 246 ± 12 W for elite male XC cyclists. They also found XC racing, like DH, is intermittent in nature, characterised by a combination of high and low power output, the magnitude and duration of which were influenced by the course terrain.

This difference may be due to sub-elite level riders being tested in the current study. Additionally, the lower mean power outputs in DH racing may also be due to a 'freewheel' effect. At high speeds minimal force may have be applied to the pedals during the efforts following periods of non-pedalling. This is potentially due to the rider being required to catch up with the speed of the rear wheel freewheel before any force is applied through the drive system.

Calculations for mean power and cadence, were performed including zero values as well as with them omitted, as the non pedalling periods of the run accounted for 55 % of overall runtime, and were therefore too significant to ignore. The longer a rider spent not pedalling or 'coasting', particularly in more technical sections, the more it would influence mean power output for the run. Analysis of results showed that the quicker riders recorded fewer zero values as a result of less time spent coasting and indeed recorded higher mean power outputs.

The variation between peak and mean power outputs is particularly evident during the initial few seconds of the run, where all riders achieved their peak power output. As with events such as downhill skiing, the effort from a static start appears vital. However, the current study found time to peak power was not related to run time. This would infer that a high level of technical ability could compensate for a lack of explosive power in the initial few seconds of a DH run, and help to minimise losses in speed due to unnecessary braking and poor line selection.

Cadence is an important determinant of power output, and can be adjusted by selecting the appropriate gear ratio at the start of the run, thereby enhancing the transfer of potential to kinetic energy. Mechanical power output in cycling is dependent upon cadence. Van Soest and Casius (2000) proposed an optimum cadence of around 130 revolutions per minute. In the current study riders achieved peak cadences of 128 ± 20 $rev.min^{-1}$ (range 99 to163 $rev.min^{-1}$), close to the recommendation of Van Soest and Casius (2000). However, the average cadence that coincided with peak power was lower, 96 ± 18 $rev.min^{-1}$. Analysis of cadences revealed the average pedalling period to be less than five seconds with an average of thirty-eight pedal 'actions' per run, though the power output and cadence varied greatly. The majority of riding time was spent with the pedals static, acting more as a support platform than a dynamic performance component. This is reflected by the low mean power output for the run, 27 ± 5 $rev.min^{-1}$.

The poor relationship between cadence and power output highlighted in the current study emphasises that for DH riders the quality of force generation would be more important than simply turning the pedals. Whilst an initial near maximal effort will accrue the necessary velocity, such efforts are not characteristic of the whole run. Average cadence was significantly related to speed. This is unsurprising, as average values would share linear characteristics in terms of speed. However, cadence was not related to power output and runtime. During periods when pedalling was possible, such as less technical sections of flatter areas of the run, riders appeared to produce efforts of around one third to one half of the peak power measured during the initial stages of the run. These efforts were not particularly strenuous and their use is debatable, suggesting more a low to moderate intensity 'spinning' effect. This may not act as a stimulus for the accretion of speed but would serve to prevent undue deceleration. As power and cadence did not significantly influence run times, it again indicates the importance of riding dynamics to overall performance in downhill. Visual observations support this supposition, as several subjects appeared to ride more 'flowingly' with seemingly minimal effort, yet still post some of the quickest run times.

The characteristics of the DH event would appear to be unlike any other form of cycling previously reported. Downhill riding utilises an entire range of performance dynamics, from no power generation to vigorous energetic efforts. Whilst the magnitude of power output varied by rider, the tempo of pedalling appeared remarkably consistent. Indeed, visual observation of time course power output curves revealed close similarity between the pedalling periods for all riders. This would support the contention that pedalling can only be undertaken at certain points during the run. Difficult technical terrain will see emphasis placed on riding dynamics rather than power generation. A balance between technical and physical dimensions of the rider's fitness would appear to be an essential component of success. Changes in course dynamics, such as wet versus dry conditions, would also ensure a variation in riding technique and subsequent energetic provision.

This dependency on the technical elements, at important parts of the run, may also explain the paradoxical relationship between heart rate and power output. A positive linear relationship between power output and heart rate is well supported. However, in the current study, heart rate showed a remarkable stability (168 $\pm$ 5 beats.min^{-1}) over the duration of the run when compared to the erratic nature of the power output response. As more than half of the average DH run time was spent not pedalling with the remainder being performed at a low to moderate intensity effort, it is surprising to identify heart rates consistently at ninety percent of maximum. Research by Stapelfeldt *et al.* (2004) into XC racing also found mean HR to account for 91 % of maximal values and were remarkably stable despite considerable fluctuations in power output.

Such inconsistency could be explained by the dynamic and isometric muscular efforts needed to overcome technical obstacles and to affect dampening of irregularities in terrain, leading to the elevated heart rates observed throughout the duration of the runs. Stapelfeldt *et al.* (2004) also stated that this disparity between HR and power might be due to the cardiovascular system not being able to respond and adapt quickly enough to the rapid changes in high and low power output. If this assumption were to be accepted, then the same would certainly be true for DH, as the changes in power magnitude occur more frequently.

Conclusions

Results from this study have shown that the performance energetics of DH riding can be classified as such. Initial very high intensity efforts are used to accelerate the rider. These are then supplemented by continual lower intensity, intermittent efforts. The contribution of these efforts to overall speed and subsequent run time remains unknown. The present study only evaluated power output and cadence and their contribution to performance in DH riding. Subsequent research may seek to investigate the contribution of upper body muscular activity to downhilling and to evaluate riding dynamics.

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HEART RATE RESPONSES TO DOWNHILL MOUNTAIN BIKING IN DOWNHILL AND CROSS COUNTRY CYCLISTS

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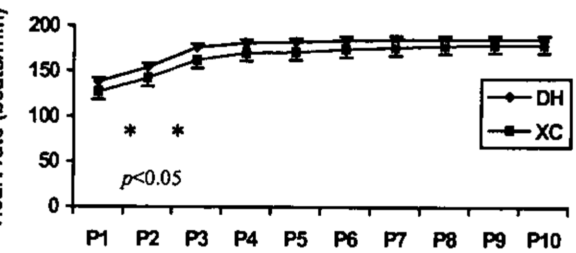
Mountain biking has become more popular as a leisure activity over the past decade (Baron, 2001). The sport has several disciplines, of which downhilling is rapidly becoming one of the most popular. Riders compete over a measured downhill course against the clock. Despite the popularity of the downhill discipline, there is a dearth of research into this area. The aim of this study was to evaluate the heart rate responses of downhillers (DH) and cross-country (XC) mountain bikers, during downhill riding.

Six DH riders (age 27.1 ± 5.4 years) and seven XC riders (age 43.0 ± 9.2 years) each performed two timed runs down a measured downhill course (distance - 1.7km, vertical interval - 180 m). Heart rates were recorded using a short-range telemetry system (Vantage NV, Polar, Kempele, Finland). The sampling rate was set to record the R-R interval. Subjects were allowed to use their own cycle (seven full suspension, six front suspension only). Mean heart rates were recorded for ten successive fifteen-second intervals (P1 to P10). Overall performance time was also recorded. An independent t-test was used to assess differences in the heart rate response, and performance time, between groups.

A One-Sample Kolmogorov-Smirnov test revealed that all test variables were normally distributed. The mean heart rate response is described in figure 1.

Figure 1. Mean heart rate response to downhill riding.



Results showed a significant difference in heart rates, by discipline, at the first and second data points ($p<0.05$ at P1 and P2). No significant differences were identified between data points at any other part of the timed trial. DH riders performed the timed run significantly faster ($p<0.05$).

The measured differences, at P1 and P2, may be due to an increased power output at the start of the runs. Though the sport sees an intermittent intensity pattern, heart rates were consistently very high. The mean heart rates for both groups were higher during downhilling than those found by research on cross-country riding (Wilber et al., 1997). Intensity may remain high due to the muscular activity of the arms and legs during the non-pedalling phases. This can help to dampen the impact of the course, and assist in manoeuvring the bicycle over obstacles. Further research using SRM power cranks will help to determine whether DH riders do produce more power than XC. The quicker times by the DH riders are more likely to be a result of greater downhill-specific riding skills. Anstiss (1997) also reported that DH riders took more risks than XC both in sport and in other aspects of their lifestyles. This risk-taking tendency of downhillers may be a factor in the faster times between groups. In conclusion, DH riders performed at a higher heart rate level than XC during the trial. Factors such as power output, skill and attitudes to risk are likely to be influential in downhilling performance.

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