

SELECTED PHYSIOLOGICAL AND PERCEPTUAL RESPONSES OF BATSMEN
DURING A SIMULATED ONE DAY INTERNATIONAL CENTURY: IMPACT ON
PERFORMANCE

BY

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ABSTRACT

Background: Very few studies have examined the demands of prolonged batting on physical, psychophysical and performance responses. **Objective:** The purpose of this study was therefore to determine the physiological and perceptual responses of batsmen scoring a simulated One Day International century. Furthermore, the impact that these responses had on batting performance were also measured. **Methods:** Seventeen male cricketers currently playing for Rhodes University or the country districts side, performed a simulated bating innings (BATEX[®]), typical of scoring a One Day international century. The BATEX[®] protocol consisted of six, five over stages (21 minutes each), with each stage matched to a specific phase of play where batsmen were encouraged to bat with the mindset of that phase. During stages one, three and five players ran at a “self-selected cruise pace” whereas during stages two, four and six players were required to run at maximum speed. At set intervals, selected physiological, perceptual and performance measures were recorded. **Results:** Most physiological responses increased and decreased accordingly with the low and high intensity stages with the exception of respiratory exchange ratio and core temperature responses. Mean physiological responses however, showed a progressive rise over time. Central ratings of perceived exertion increased as a function of intensity and duration. Sprint times got slower as the protocol progressed, while accuracy (impact accuracy) improved significantly ($p < 0.05$) after stage one and then stabilised for the remainder of the protocol. **Conclusion:** The simulated batting protocol significantly impacted the physiological and perceptual responses over time. This was due to both the intensity and the duration of the work-bout. Furthermore, the increased physiological load placed on the batsmen significantly impacted the physical performance of the batsmen. An increase in sprint times (players getting slower) towards the end of the protocol may indicate the presence of physical fatigue. This physical fatigue did not however seem to impact the batsmen cognitively as accuracy improved after the first stage and then remained constant over time.

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CHAPTER I

BACKGROUND TO STUDY

INTRODUCTION

Cricket is one of the most popular sports in the world with the game having changed dramatically over the last three centuries (Patel *et al.*, 2002). The first form of the game, five day Test matches, has evolved into one day international cricket (50 over games), and more recently there has been the introduction of the twenty over format of the game. As a result, cricketers of the modern era face increasing demands both physically and psychologically, and are constantly under pressure to perform (Stretch, 2003). The fact that cricket has become a profession and is no longer just a hobby or sport means that it is crucial that players are injury-free and match fit for the larger part of the season. Cricket has received very little research attention compared to other international sports, especially with respect to the physiological or physical demands of match-play (Duffield and Drinkwater, 2008). This may be due to the fact that the game is intermittent in nature, and therefore it is difficult to study all aspects of the game (Christie *et al.*, 2008).

It is well known that increases in the volume and intensity of participation may lead to an increase in injuries associated with all parts of the game including bowling, batting and fielding (Mansingh, 2006). With specific reference to batting, most injuries to batsman are lower limb injuries (54.4%), the most prevalent sites being the hamstrings, quadriceps, knees and ankles (Stretch, 2003). The head, neck and face are also often injured during batting, and 27% of these injuries occur due to players batting for extended periods of time (Stretch, 2003). Therefore, top-end batsmen need to be well trained not only to avoid direct injuries from being struck by the ball, but also to avoid indirect and overuse injuries as a result of repetitive training and game play which may impact the physical demands placed on them (Stretch *et al.*, 2000).

Although there are limited data on the physical demands of batting, the first physiological study on cricket was conducted by Fletcher (1955), who predicted the average energy expenditure of international cricketers in the 1953 Ashes test series. This study concluded that cricket was a physically undemanding sport. In 1993 Gore and colleagues conducted another study on cricket and looked more specifically at batting in a One Day International (ODI). They found that the physiological demands of batting in an ODI are substantial, which opposed the findings of Fletcher (1955). Later investigations in our laboratory showed heart rate responses ranging between 136 and 159 b.t.min^{-1} , oxygen uptake responses between 26.70 and 26.93 $\text{ml.kg}^{-1}.\text{min}^{-1}$ and energy expenditure responses between 2536 and 2776 kJ during short-duration, high-intensity batting protocols (Christie *et al.*, 2008; King, 2002; Pote and Christie, in press). More recently, studies have been conducted during Twenty/20 and 50 over matches (Petersen *et al.*, 2010; Nicholson *et al.*, 2009). Heart rate responses were recorded between 149 and 167 b.t.min^{-1} for Twenty/20 matches and between 139 and 154 b.t.min^{-1} during 50 over matches (Petersen *et al.*, 2010; Nicholson *et al.*, 2009). These responses were very similar to those recorded during studies in our laboratory, showing the reliability of laboratory based protocols. However, these protocols have been criticized because they are very short in duration and very high in intensity and it is questioned whether this is applicable to real time game play. Batsmen alter their intensity of effort depending on the circumstances and probably based on how they are feeling at any given point in time. One example of this is scoring a century when a batsman alters intensity of effort intermittently depending on circumstance and perception of effort. Interestingly however, no extensive studies have looked at the energy cost associated with scoring a high volume of runs, such as centuries, where a batsman is not constantly running at full pace and where there is an interplay between duration and intensity. One study has looked at select physiological responses (Houghton *et al.*, 2011a) but this needs to be expanded further.

Noakes and Durandt (2000) predicted that a batsman scoring an ODI century runs 25 singles, 10 twos, 5 threes, 10 fours and runs a total of 3.2 km in 8 minutes, meaning a running speed of 24 km.h^{-1} ; however, this analysis was only an estimate. This earlier estimation was followed more recently with an in-depth analysis which showed that when scoring a ODI century, a batsman runs an average of 40 singles,

8 twos, 3 threes and hits an average of 7 fours and 2 sixes (Duffield and Drinkwater, 2008). It was also noted that the batsman spends approximately 136 minutes at the crease. From this analysis it was seen that the amount of singles run per batsman while scoring a century (40), was significantly higher than the estimation (25) of Noakes and Durandt (2000). The most recent study focused on the development of a batting exercise protocol (BATEX[®]), designed to simulate the physical demands of scoring an ODI century (Houghton *et al.*, 2011a). Houghton *et al.* (2011a), using the BATEX[®] protocol, showed a mean heart rate of 130 $\text{b}\cdot\text{min}^{-1}$ and a tympanic temperature of 35.9 °C. Obviously however, the lower intensity in the century protocol was offset by the longer duration, and the protocol was claimed to be a more accurate reflection of real time play (Houghton *et al.*, 2011a). However, physiological data were limited to heart rate, tympanic temperature and sweat rate, so there is a need for more detailed physiological assessment during this protocol.

In terms of batting performance, Houghton *et al.* (2011b) looked at good bat-ball contacts as well as running-between-the-wickets-performance and stated that this may be used to better understand the impact of fatigue during batting for extended periods of time. It was also concluded in this study that sprint times are a reliable indicator of running-between-the-wickets performance over a prolonged batting simulation (Houghton *et al.*, 2011b). Stretch *et al.* (2004) looked at the position of impact of the ball striking the bat and found that batsmen with greater skill tend to strike the ball more towards the centre and inner surface of the bat. However, this latter study did not involve batting for extended periods of time, such as scoring a century. Furthermore, no studies to date have looked at the link between the physiological demands of the game and batting performance, especially over long periods of time. Although Houghton *et al.* (2011b) did investigate sprint times, this was the only performance response measured. It is therefore important to understand how the physiological demands of scoring an ODI century impacts batting performance, especially in terms of running (sprint times) and skill (accuracy of the impact of the ball on the bat)

STATEMENT OF THE PROBLEM

The physiological responses of batsmen, especially over extended periods of time, have received very little research attention. More specifically, no research has focused on the effects of an increased physiological load on a batsman's performance. By understanding the physiological demands it may be possible to implement specific and scientifically based training programs to improve performance and reduce the risk of injury. The purpose of this study was therefore to determine the effect of a simulated ODI century on a batsman's physiological and perceptual responses, and to determine whether a change in these responses would impact performance.

RESEARCH HYPOTHESIS

It was expected that the physiological, perceptual and performance responses during the simulated one day international batting work-bout would be significantly impacted.

STATISTICAL HYPOTHESIS

PHYSIOLOGICAL HYPOTHESES

1. The null hypothesis proposed that during the simulated century batting protocol, there would be no difference in the physiological responses over time:

- a) Heart rate, oxygen uptake and energy expenditure

- (i) Heart rate:

$$H_0: \mu_{HR1} = \mu_{HR2} = \mu_{HR3} = \mu_{HR4} = \mu_{HR5} = \mu_{HR6}$$

$$H_a: \mu_{HR1} \neq \mu_{HR2} \neq \mu_{HR3} \neq \mu_{HR4} \neq \mu_{HR5} \neq \mu_{HR6}$$

- (ii) Oxygen uptake and energy expenditure

$$H_0: \mu_{VO_2, EE1} = \mu_{VO_2, EE2} = \mu_{VO_2, EE3} = \mu_{VO_2, EE4} = \mu_{VO_2, EE5} = \mu_{VO_2, EE6}$$

$$H_a: \mu_{VO_2, EE1} \neq \mu_{VO_2, EE2} \neq \mu_{VO_2, EE3} \neq \mu_{VO_2, EE4} \neq \mu_{VO_2, EE5} \neq \mu_{VO_2, EE6}$$

b) Breathing frequency, tidal volume, minute ventilation and respiratory exchange ratio

(i) Breathing frequency:

$$H_0: \mu_{Rf1} = \mu_{Rf2} = \mu_{Rf3} = \mu_{Rf4} = \mu_{Rf5} = \mu_{Rf6}$$

$$H_a: \mu_{Rf1} \neq \mu_{Rf2} \neq \mu_{Rf3} \neq \mu_{Rf4} \neq \mu_{Rf5} \neq \mu_{Rf6}$$

(ii) Tidal volume:

$$H_0: \mu_{VT1} = \mu_{VT2} = \mu_{VT3} = \mu_{VT4} = \mu_{VT5} = \mu_{VT6}$$

$$H_a: \mu_{VT1} \neq \mu_{VT2} \neq \mu_{VT3} \neq \mu_{VT4} \neq \mu_{VT5} \neq \mu_{VT6}$$

(iii) Minute ventilation:

$$H_0: \mu_{VE1} = \mu_{VE2} = \mu_{VE3} = \mu_{VE4} = \mu_{VE5} = \mu_{VE6}$$

$$H_a: \mu_{VE1} \neq \mu_{VE2} \neq \mu_{VE3} \neq \mu_{VE4} \neq \mu_{VE5} \neq \mu_{VE6}$$

(iv) Respiratory exchange ratio:

$$H_0: \mu_{RER1} = \mu_{RER2} = \mu_{RER3} = \mu_{RER4} = \mu_{RER5} = \mu_{RER6}$$

$$H_a: \mu_{RER1} \neq \mu_{RER2} \neq \mu_{RER3} \neq \mu_{RER4} \neq \mu_{RER5} \neq \mu_{RER6}$$

c) Core temperature and sweat loss

(i) Core temperature:

$$H_0: \mu_{Tc1} = \mu_{Tc2} = \mu_{Tc3} = \mu_{Tc4} = \mu_{Tc5} = \mu_{Tc6}$$

$$H_a: \mu_{Tc1} \neq \mu_{Tc2} \neq \mu_{Tc3} \neq \mu_{Tc4} \neq \mu_{Tc5} \neq \mu_{Tc6}$$

(ii) Sweat loss:

$$H_0: \mu_{ss} = \mu_{se}$$

$$H_a: \mu_{ss} \neq \mu_{se}$$

PERCEPTUAL HYPOTHESIS

2. During the batting protocol there would be no differences in the perceptual responses over time:

$$H_0: \mu_{PER1} = \mu_{PER2} = \mu_{PER3} = \mu_{PER4} = \mu_{PER5} = \mu_{PER6}$$

$$H_a: \mu_{PER1} \neq \mu_{PER2} \neq \mu_{PER3} \neq \mu_{PER4} \neq \mu_{PER5} \neq \mu_{PER6}$$

PERFORMANCE HYPOTHESES

3. The null hypothesis proposed that there would be no difference in the performance responses over time during the simulated batting protocol:

- a) Accuracy of the impact of the ball on the bat:

$$H_0: \mu_{a1} = \mu_{a2} = \mu_{a3} = \mu_{a4} = \mu_{a5} = \mu_{a6}$$

$$H_a: \mu_{a1} \neq \mu_{a2} \neq \mu_{a3} \neq \mu_{a4} \neq \mu_{a5} \neq \mu_{a6}$$

- b) Sprint time between the wickets (stages 2, 4 and 6):

$$H_0: \mu_{st2} = \mu_{st4} = \mu_{st6}$$

$$H_a: \mu_{st2} \neq \mu_{st4} \neq \mu_{st6}$$

Where: HR is heart rate

VO₂ is oxygen uptake

EE is energy expenditure

Rf is breathing frequency

VT is tidal volume

VE is minute ventilation

RER is respiratory exchange ratio

Tc is core temperature

ss is sweat loss at the start of the protocol

se is sweat loss at the end of the protocol

a is the accuracy of the impact of the ball on the bat

st2 is the sprint time between the wickets during stage 2 of the protocol

st4 is the sprint time between the wickets during stage 4 of the protocol

st6 is the sprint time between the wickets during stage 6 of the protocol

PER is the perceptual responses

1, 2,3,4,5,6 is the number of the stage

Physiological responses were assessed by heart rate (HR), breathing frequency (Rf), tidal volume (VT), minute ventilation (VE), respiratory exchange ratio (RER) oxygen uptake (VO_2), carbon dioxide production (VCO_2) energy expenditure (EE), sweat loss and core temperature (T_c). Perceptual responses were monitored with the use of Borg's (1998) ratings of perceived exertion (RPE) scale. The performance responses were assessed using an accuracy measure (accuracy of the impact of the ball on the bat) as well as sprint time between the wickets (during stages 2, 4 and 6).

DELIMITATIONS

The sample was delimited to 17 male batsmen currently playing for the Rhodes University Cricket Club and Eastern Province Country Districts cricket team. Players were between the ages of 19 and 27 years and were considered suitable for the study due to the fact that they participated in cricket activity on a regular basis. The main aim of the study was to determine the physiological and perceptual responses of batsmen while scoring an ODI century and to determine whether these responses had any impact on batting performance. Players were therefore required to complete a laboratory based, simulated batting protocol consisting of 6 stages (5 overs in each stage) of varying intensities. The protocol was designed to mimic the demands placed on a batsman when scoring an ODI century.

Players were required to attend two sessions. During the first session the protocol was explained to the participants and players were habituated to the equipment to be used in the study. The risks and potential benefits of the study were also explained to the players, both verbally and in writing, and all participants were asked to fill in a physical activity screening questionnaire and to complete a consent form. During this session basic demographic and anthropometric data were recorded and players were given the CoreTemp[®] pill to swallow before the experimental protocol.

During the second session, players were required to complete the simulated batting protocol. Testing took place in a laboratory setting therefore ensuring that extraneous variables did not impact the physiological, perceptual and performance responses measured. These responses were collected at set time intervals during the two-and-a-half-hour batting protocol. Testing took place immediately post-season to ensure adequate training status, but also to ensure the players were well rested and free of any injuries.

LIMITATIONS

Although every effort was made to control any extraneous variables that may have affected the investigation, there were a number of limitations. These should therefore be taken into account when examining the findings of the study:

The study took place in a laboratory setting and was therefore not able to take into account all the aspects of a cricket game, such as the varying environmental conditions (wind, rain and sun). Furthermore, the impact that the crowd has on a batsman during a normal ODI could not be replicated. However, verbal encouragement was given to all batsmen when necessary.

Although all participants were batsmen either from the Rhodes University Cricket Club, or from the Country Districts cricket team, the training status of the players could not be controlled. However, testing took place after the completion of the cricket season, meaning players were well trained and rested.

The speed at which the players completed the low intensity (stages 1, 3 and 5), although self-selected, differed between each individual.

The mental and cognitive aspect of batting for extended periods of time was not examined, as the main aim of the study was to determine the physical cost of batting for long periods of play. However, the importance of these aspects cannot be underemphasized.

Although players were given pre-test instructions, the researcher had no control over whether these instructions were followed or not. On arrival at the testing venue participants were asked if the instructions had been followed accurately and concisely. If not, no testing took place.

Players were required to wear a mask (k4b²), thus the use of a protective batting helmet was not possible. Although the participants were at no risk of injury, a helmet may have affected the responses collected, especially core temperature measures.

The end-point of the batting protocol was known by the players and this may have allowed the implementation of certain pacing strategies. In an ODI, batsmen do not know how long they are going to bat for and thus they are less likely to adopt a pacing strategy.

The electronic bat used for the accuracy measure was heavier than a standard bat (1.46 kg) due to the equipment placed on the back of it, as well as the protective foam and tape. This may have affected the way the players timed the ball. Furthermore, the fact that the batsmen switched between the electronic bat and their own during the protocol, may also have affected performance measures.

Although the rest periods between overs were not measured, oxygen uptake data were averaged across the stages for each over. The analyses thus include both recovery and work periods, which is a limitation in itself.

The use of a bowling machine is not an accurate representation of an actual bowler. This may have affected responses as usually a batsman uses visual cues from the bowler's run-up and delivery action to determine a suitable shot to play

The additional mass of the k4b² on the players may have affected the physiological responses that were recorded.

The ball feed location (line and length) from the bowling machine was not recorded, therefore impacting the consistency at the start of each stage when the electronic bat was used.

Due to equipment constraints, a single beam timing gate system was used to measure sprint times instead of a double beam system. This made it difficult to compare sprint times from other studies that used different timing systems.

CHAPTER II

REVIEW OF LITERATURE

NATURE OF THE GAME

Cricket has evolved significantly over the past 300 years since first being played in the early seventeenth century. The first laws of the game were put into practice in 1744 and these laws continue to form the basis of the laws being used today (Woolmer *et al.*, 2008). According to Noakes and Durandt (2000), international cricket is changing dramatically as it seeks to attract a more global audience, and as a result of this change, cricketers of the modern era are faced with greater physiological demands. A study by Fletcher (1955), where the average energy expenditure of international cricketers was predicted, resulted in the idea that cricket was a physically undemanding sport. This has been criticized to a large extent as cricketers nowadays are subjected to much longer seasons consisting of five day Test matches, one day internationals (ODIs) and twenty/20 matches.

Test match cricket was the first form of the game and is played over five days, with three sessions consisting of two hours each. The sessions are divided by a 40 minute lunch break and a 20 minute break for tea in the afternoon. There is also a 5 minute drinks interval during each two hour session. The bowling team is required to bowl 90 overs per day but this depends to a large extent on the weather. During a test match no fielding restrictions are implemented.

One day internationals, unlike Test matches, always end with a result in a single day. They consist of two sessions of 50 overs each (3.5 hours per session) with a 40 minute break between the two sessions for lunch or dinner (depending on whether the game is a day/night). There are also drinks intervals within each session of 50 overs. Fielding restrictions are required during an ODI during certain phases of the game.

The introduction of Twenty/20 (T20) cricket has had an enormous effect on the modern game. Tournaments such as the Indian Premier League (IPL) and the T20 World Cup have attracted a large number of spectators not normally associated with

the game and the focus is slowly shifting from Test matches and ODIs to Twenty/20. Many believe that this type of game is much more entertaining due to the number of boundaries hit and the fielding restrictions. Twenty/20 cricket is the most modern form of the game and consists of two sessions of 20 overs each. The changeover from batting to bowling in this form of the game is much shorter than an ODI and in some forms of Twenty/20 games a 10 minute strategic timeout is allowed by both the batting and bowling sides during certain overs of the match. It is thought that this form of the game requires much higher levels of fitness.

The fact that the game has evolved to such a large extent means that the demands placed on the players nowadays are significantly greater than when the game was first introduced. Thus it is highly important to gain an understanding of these demands.

INJURIES IN CRICKET

Nowadays, players are very susceptible to injuries during all stages of the season. Studies have shown that approximately 28-72% of cricketers sustain between 1.61 and 1.91 injuries per season (Stretch, 2003). Furthermore, the high intensities and workloads that players are exposed to at the elite level, means that injuries are quite common and occur more often (Orchard *et al.*, 2010). It is therefore very important that injury surveillance, at all levels of cricket, is carried out to provide successful injury prevention (Orchard *et al.*, 2006).

There are a several ways in which an injury can be defined in the context of cricket. Firstly, it may be defined as the onset of pain or disability caused while training for, or playing, cricket that causes a player to seek medical attention (Stretch, 2007). It may also be defined as a medical condition that prevents a player being available for selection for a match or causes a player not to be able to bat, bowl or keep wicket during a match (Stretch, 2007). No matter how an injury is defined however, it is quite clear that any injury is detrimental to a player's health and performance. Most studies have shown that bowlers are the most susceptible to injuries (Stretch, 2003), however with the longer seasons that players are now faced with, as well as the introduction of new forms of the game, all players (batsmen, bowlers and fielders)

have to be well trained and physically prepared for the season. According to Stretch *et al.* (2000), the modern batsman needs to be very 'fit' not only to avoid being hit by the ball (direct injury), but also to avoid indirect and overuse injuries that occur as a result of repetitive training, as the game of cricket becomes more explosive in nature. These types of injuries can be referred to as intrinsic injuries which are characterised by the onset of discomfort or lack of mobility (Woolmer *et al.*, 2008). Usually these injuries are caused by the repetition of certain movements to such a point that damage is done to the muscles, joints and bones that are involved in the movement (Woolmer *et al.*, 2008). An example of how an intrinsic injury could occur would be running between the wickets. While it was originally thought that batsmen suffered a relatively small number of intrinsic injuries, Woolmer *et al.* (2008) state that these injuries are increasingly being found in both batsmen and fielders playing at the elite level and this is a result of the large amount of cricket that is being played.

Although cricket is a widely renowned international team sport, only four major cricket playing nations have collected long-term injury data. These nations are Australia, South Africa and England, as well as the West Indies, where international and domestic cricket scenes were analysed between June 2003 and December 2004 (Stretch, 2007; Mansingh *et al.*, 2006). However, while different sets of data often show definite trends, it is not always possible to make direct comparisons of data collected in different countries (Stretch, 2007). The Cricket Boards of the International Cricket Council therefore developed a standard data collection and reporting format that has been used to standardise the definitions and reporting of injuries (Mansingh *et al.*, 2006). This form of reporting and data collection was used in the study of injuries in West Indies cricket between 2003 and 2004.

Injury data for Australian state and national cricketers were collected retrospectively between 1995 and 1998 and then prospectively between 1999 and 2005 (Stretch and Raffan, 2011). In total 886 injuries were recorded. Of these, 92% were new injuries, with 8% being recurrent and 52% occurring during major matches (Stretch and Raffan, 2011). The majority of the injuries occurred while bowling (45%) with 49% of the injuries being in the lower limbs. According to Stretch (2003), injuries to the soft tissues of the lower limbs are primarily due to bowling, running between the wickets during batting and running to field the ball. The highest incidence of injuries

occurred during ODIs, with a mean incidence rate of 59.8 injuries per 10 000 player hours (Stretch and Raffan, 2011).

The study performed in South Africa looked at injury patterns occurring between 1998 and 2004, and it was found that a total of 1606 injuries occurred in 783 cricketers (Stretch, 2007). All cricketers were either provincial or national players and the injuries were reported by the physiotherapists and doctors working with the specific teams (Stretch, 2007). Sixty five percent of injuries were first time injuries, with 22% being carried over from the previous season and 13% recurring in the same season (Stretch and Raffan, 2011). Most of the injuries were classified as acute injuries (65%), with chronic and acute-on-chronic injuries accounting for 23% and 12% of all injuries, respectively (Stretch and Raffan, 2011). Once again, bowling resulted in 40% of all injuries with 55% of these being lower limb injuries. Other injuries were caused by activities such as being struck by the ball, running between the wickets and training for cricket, batting for extended periods of time and playing other sports (Stretch and Raffan, 2011).

A retrospective study performed in England between 1985 and 1995 on 54 county cricketers showed that a total of 990 injuries occurred with an incidence rate of 57.4 injuries per 1000 days played (Stretch, 2007). According to Stretch and Raffan (2011) most injuries occurred in the early parts of the season and once again bowlers were the most susceptible to injury, followed by all-rounders, batsmen and wicketkeepers. It was also found that on average, 49.4 batsmen were injured every 1000 days. As in the Australian and South African studies, the majority of the injuries (45%) occurred within the lower limbs and the areas that were most affected by injury were the thigh and calf (25%), fingers (14%) and the lumbar spine (11%) (Stretch and Raffan, 2011).

The study performed by Mansingh *et al.* (2006) on West Indies cricket players between 2003 and 2004 was the first to use the standard data collection and reporting format. Injuries from both domestic and international teams were considered. From this study it was reported that most injuries occurred in the West Indies test match side and the one day international team (Mansingh *et al.*, 2006). Average injury incidence was 48.7 and 40.6 per 10 000 hours played for Test matches and ODIs respectively, which was slightly lower than the incidence

recorded for Australian cricketers. Table I shows the time, in days, lost due to injury in relation to the main role of the player.

Table I: Time lost (days) due to player injury, adapted from Mansingh et al. (2006)

	1-3 days	4-7 days	8-14 days	15-21 days	>21 days	TOTAL
All rounder	2	0	0	0	3	5
Batsman	8	0	3	1	8	20
Wicketkeeper	0	1	0	0	1	2
Fast bowler	5	2	4	0	9	20
Medium pace bowler	1	0	0	0	0	1
Spin bowler	0	1	0	0	1	2
TOTAL	16	4	7	1	22	50

Most injuries (80%) were sustained by fast bowlers and batsmen with 8 batsmen and 9 bowlers being ruled out due to injury for more than 21 days (Table I). Overall, a total of 20 batsmen and 20 bowlers were injured. For all the injuries that occurred, 26% were muscle strains, 24% were ligament strains and stress fractures and 10% were due to other fractures (Mansingh *et al.*, 2006). These statistics show that injuries are becoming a major concern for batsmen, bowlers and fielders. Therefore it is important to understand the role of each specialised position and more specifically in this case, batting.

BATTING

The action of hitting a cricket ball with a cricket bat in order to score runs or to prevent the loss of a person's wicket is known as batting. The batsman is known as the player who is currently batting and the shot or stroke is the act of hitting the ball. Terms such as batsman, or specialist batsman, can also be used to describe players that specialize in batting. During a single innings, two batsmen from the same team bat. The batsman facing the bowler is known as the striker while the batsman at the bowler's end is known as the non-striker. Once a batsman is dismissed or given out,

they are replaced by another batsman. This process continues until the end of the innings or until all batsmen are out, after which it is the other team's turn to bat.

The strategies and tactics batsmen use may vary to a large extent, depending on the type of match being played or the situation of the current game. The main aim is to not lose wickets and to score as many runs as possible in the shortest amount of time. This however may result in some risky shots being played which can increase the chance of the batsman getting out. The situation the batsman is in determines on whether they play conservatively by keeping their wicket or whether they attempt to score runs as quickly as possible and are not concerned with the possibility of being dismissed. Runs can be scored either by 'hitting out' (trying to score boundaries) or by sprinting singles between the wickets. In either case, the physiological demands of batting increase, as does the risk of injury or performance decrement. The fact that batting requires a lot of running means that it is characterised by the ability to repeat high-intensity short duration efforts after short recovery periods, which is known as repeated sprint ability (RSA) (Buchheit *et al.*, 2010).

There are also a number of different batting strokes, such as the cover drive, hook shot and sweep shot, that batsmen may implement depending on the type of bowling (fast, medium or spin) or on the current situation of the match (attacking or defensive). According to Mitchell *et al.* (2006), batters need a much greater tactical understanding and associated skills in order to attack the different types of deliveries that a bowler may produce. Furthermore, Mitchell *et al.* (2006) also states that batters need a greater offensive array of strokes or shots, when the bowling technique becomes more advanced and when specific field placements are introduced.

PHYSICAL CHARACTERISTICS OF BATSMEN

Anthropometry has been used for a number of decades to determine the relationship between body structure and the specialised functions required to perform a certain task (Koley, 2011). Every individual is unique, and the fact that the extent of human variability is large, means that each individual can never be the same. Some sports

events are therefore suitable to individuals having a specific physique, and it has been established that certain anthropometric profiles or physical characteristics determine whether an individual is suitable to compete at a high level in a certain sport (Koley, 2011).

While some sports have been studied extensively, the morphological and anthropometrical characteristics of cricketers, or more specifically batsmen, have been under-researched (Stretch *et al.*, 2000). Of the limited research that has been conducted, most studies have focused on cricket in general rather than batsmen in particular (Stretch, 1987). According to Stretch *et al.* (2000), most cricketers have a tall athletic build, however there are distinct morphological differences between batsmen, bowlers and all-rounders. Anthropometrically, batsmen tend to be shorter and lighter than bowlers, but have a fat mass that is relatively greater than bowlers, whereas bowlers have been shown to have a greater absolute muscle and bone mass compared to batsmen (Stretch *et al.*, 2000). A study performed by Gore (2000) that looked at the anthropometric characteristics of Australian cricketers showed that bowlers were, on average, at least 200 mm taller than batsmen. On average bowlers had a stature of 1892 mm and batsmen an average stature of 1689 mm. This may be due to the fact that for batting, size may not be advantageous, whereas it is preferred if bowlers are large and tall (Stretch *et al.*, 2000). In general, somatotype ratings of 2.5-5.3-2.1 and 3.1-5.5-2.0 for provincial players have been recorded and a rating of 3.8-4.4-2.4 has been recorded for cricketers at club level (Stretch, 1987; Stretch, 1990; Peens, 1996). When it comes to batsmen in particular, ratings of 2.5-5.2-2.0 and 3.0-5.7-2.0 have been documented for provincial batsmen and a rating of 3.7-4.5-2.4 has been recorded for club batsmen (Stretch, 1987; Stretch, 1990; Peens, 1996). From these studies it was found that batsmen can be characterised as endo-mesomorphs (Stretch *et al.*, 2000). Another comparison performed on male club cricketers also showed different somatotype ratings, but overall players were also characterised as endo-mesomorphs (Ackland *et al.*, 2009). However, Carter and Heath (1990) classified cricketers in general as meso-endomorphs, but stated that the majority of people playing team sports could be classified as endo-mesomorphs. It has to be taken into account though that Stretch *et al.* (2000) and Peens (1996) used South African cricket players, whereas the rating shown by Carter and Heath (1990) was as a result of using a number of

different samples. Somatotype ratings are therefore highly dependent on different sample groups (nationality, race, sex) as well as the training status of the sample group (club vs provincial vs national players).

Noakes and Durandt (2000) also looked at the physical characteristics of cricketers, more specifically body fat percentage. Working with the South African cricket team preparing for the 1999 World Cup, it was found that 11 of the 15 players that competed were actually highly proficient in other sports at national, provincial and schoolboy levels. These sports included rugby, hockey and squash, which are all intermittent in nature. When body fat percentage of cricket players and rugby players were compared it was found that both groups of players had similar values (approximately 12 percent body fat), with loose forwards having a slightly higher measure (Figure 1).

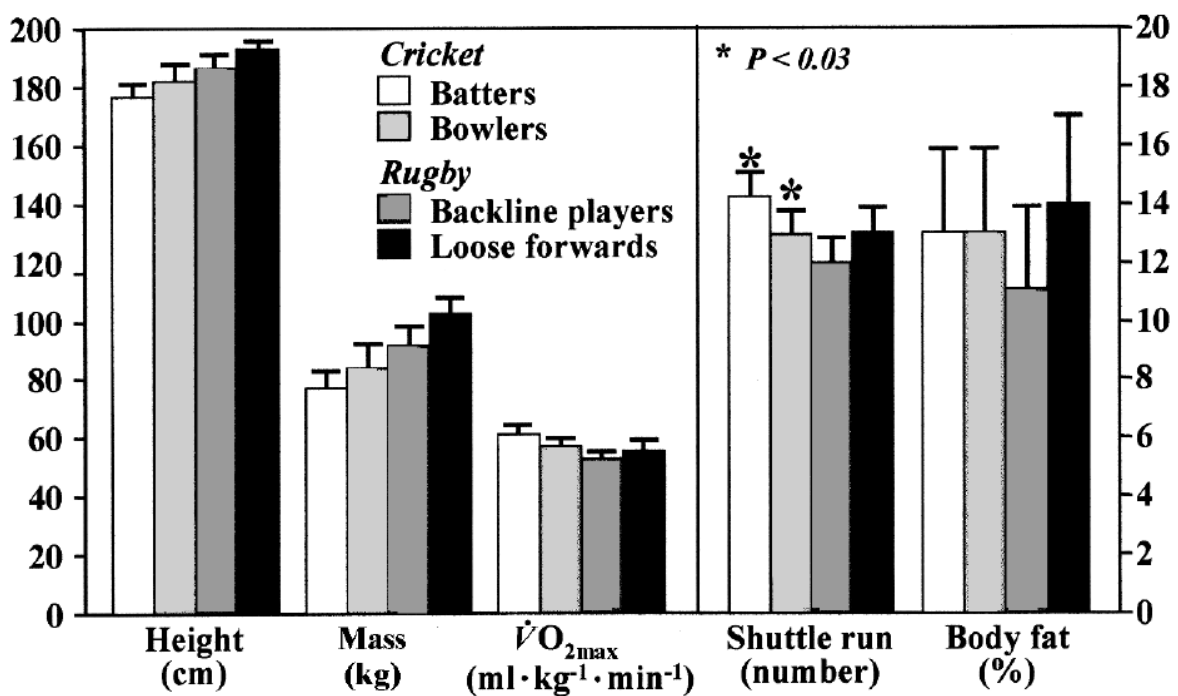


Figure 1: Physical and physiological characteristics of South African cricketers and rugby players (from Noakes and Durandt, 2000).

This value was similar to the body fat percentages recorded by Christie *et al.* (2008) and King (2002) for batsmen (12.4% and 11.9% for university and provincial players respectively). In terms of body mass both bowlers and batsmen were lighter than backline players and loose forwards, and when bowlers were compared to batsmen it was found that bowlers were taller and heavier, as observed by Stretch *et al.*

(2000), but batsmen were smaller, lighter and faster (Noakes and Durandt, 2000). However, when the physiological characteristics of cricketers and rugby players were compared, there were no real differences between the groups, even though the physical demands of rugby are considered to be much higher (Noakes and Durandt, 2000). From these results it was concluded that in terms of South African cricketers and rugby players, batsmen and bowlers are just as 'fit' or well trained as international rugby players (Noakes and Durandt, 2000). It was also concluded that the only physical characteristic that was different between the two groups was that cricketers were lighter and smaller than rugby players (Noakes and Durandt, 2000). So, the physical demands of cricket and rugby may be a lot more similar than currently believed. However, this study was conducted using only the South African national cricket and rugby teams, and these results may vary according to different countries.

THE PHYSIOLOGICAL REQUIREMENTS OF BATTING

Batting in cricket often requires short bouts of high-intensity sprints, usually less than six seconds, and because of these sprints there is an increase in muscular activity (especially in the lower limbs), which contributes to the physiological load placed on batsmen (King, 2002). However, the amount of research that has been conducted on batsmen is extremely limited. Most of the studies on batsmen have looked at the injuries that occur during batting and very few studies have looked at the physiological demands of cricket or the physiological, biomechanical and anthropometric attributes of professional cricketers (Noakes and Durandt, 2000). There is also a need to look at these responses over time as many of the earlier studies have focused on short-duration high-intensity work-bouts.

The first study that looked at the physiological demands of the game was conducted by Fletcher (1955). He collected data during the 1953 ashes test series between Australia and England and these data were used to try to predict the average daily energy expenditure of the players involved in the series. It was calculated that 100 hours of actual play took place during the series (five Test matches) during which 4363 runs were scored from a total of 1833 overs, thus 43.6 runs were scored per hour. Of these, it was shown that 26.6 were run by the batsmen and the rest were a

result of the ball being hit to the boundary (Fletcher, 1955). Considering that each batsman ran 20 m per run, Fletcher (1955) stated that each batsman would have run $500 \text{ m}\cdot\text{h}^{-1}$ when batting. From this analysis it was calculated that the 'idealized' batsmen in the 1953 Ashes series batted for 38.50 minutes and scored an average of 14 runs. Bowlers and fielders were also analysed and the overall conclusion was that the average cricketer, with a body surface area of 1.80 m^2 , expends approximately $650 \text{ kJ}\cdot\text{h}^{-1}$ (Fletcher, 1955). Therefore the mean energy expenditure of the average batsman in test cricket was lower than the energy expenditure required walking at a pace of $6 \text{ km}\cdot\text{h}^{-1}$. This led to the perception that cricket is a physically undemanding sport. However, it needs to be taken into account that the game has changed significantly since 1955 and Fletcher's study investigated the demands of test match cricket specifically. These demands are different from the physiological demands associated with ODIs or twenty/20 matches (Petersen *et al.*, 2010). His measures also took into account time spent sitting when not out in the field.

In 1993, Gore *et al.* (1993) looked at the overall demands of the game, but focused more specifically on batting. It was found that the mean heart rate during a day of cricket was approximately $128 \text{ bt}\cdot\text{min}^{-1}$ for batsmen and fielders, but heart rates can reach as high as $190 \text{ bt}\cdot\text{min}^{-1}$ for bowlers for short periods of time. It was also found that rectal temperature reached a peak value of $38.30 (\pm 0.02) ^\circ\text{C}$, indicating that players were exercising at an intensity of approximately $60\% \text{ VO}_{2\text{max}}$ (Gore *et al.*, 1993). Furthermore, Noakes and Durandt (2000) estimated the peak activity of a batsman during an ODI, and from this estimation it was deduced that the physiological demands of batting during an ODI are more substantial than originally thought. It was also found that South African international batters had a higher predicted $\text{VO}_{2\text{max}}$ than bowlers, based on a 20m shuttle run (Bartlett, 2003). It was therefore concluded that the idea of cricket being a leisurely activity is 'clearly fallacious for international batters' (Bartlett, 2003).

After 1993, a study done in our laboratory by King (2002) focused mainly on thermoregulation and the effect of protective gear worn by batsmen on physiological perceptual and performance responses. The work-bout was based on observations of matches played at the 1999 Cricket World Cup as well as from specific high scoring ODI innings played between 1991 and 2001. A high-scoring game was

when more than 260 runs were scored in one innings. Players were required to bat facing deliveries that were bowled by an assistant, receiving one delivery every 30 seconds for a total of seven overs (42 balls). After every third delivery the batsman was required to complete a full shuttle run at full pace between two popping creases which were set 17.68 m apart (length of a cricket pitch). The two by two singles run per over, which made up 28 runs in all, simulated the high work rate that was most likely to be achieved after the 15th over in a high-scoring one day international. Thirty second periods of no activity were also allowed between deliveries to simulate the time taken for the bowler to walk back to his mark, and the 1 minute break between each over was reflective of a change in bowling. Although the main focus of the study was on thermoregulation, heart rate responses were recorded during the 7-over simulated work-bout and it was found that heart rate reached an average of 136 (± 13.00) $\text{bt}\cdot\text{min}^{-1}$. It was also found that heart rate in the final over of the protocol was significantly higher (151 ± 11.00 $\text{bt}\cdot\text{min}^{-1}$) when batsmen performed the protocol in high temperatures (23.80 ± 2.20 °C) wearing full cricket kit, than when the protocol was performed in low temperatures (13.30 ± 1.90 °C) without wearing full cricket kit (145 ± 11.00 $\text{bt}\cdot\text{min}^{-1}$). This suggests that the protective gear worn in cricket in combination with the environmental conditions has an impact on a batsman's physiological responses (King, 2002). Furthermore, King (2002) also measured skin and forehead temperatures of batsmen and recorded mean values of 33.69 (± 1.24) °C and 35.38 (± 1.60) °C, while sweat rate reached values as high as 0.93 $\text{L}\cdot\text{h}^{-1}$. However, it was only in 2008 that a more in-depth analysis of the physiological responses of batting occurred.

Also in our laboratory, Christie *et al.* (2008) looked at selected physiological responses during batting in a simulated cricket work-bout and utilised the same work-bout as King (2002). Table II represents the physiological responses elicited by the batsmen. The physiological responses that were assessed included heart rate, breathing frequency, tidal volume, ventilation, oxygen uptake and metabolic carbon dioxide production. It was found that all the physiological responses increased significantly from the first to the second over and then stabilised. This excluded heart rate which continued to increase significantly until the end of the third over, after which it stabilized. According to Christie *et al.* (2008) this was due to factors such as emotional state and food intake. From this study it can be seen that

the mean heart rate of the batsmen was 145 (± 10.80) $\text{bt}\cdot\text{min}^{-1}$ while VO_2 reached a mean value of 26.70 (± 1.40) $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. The fact that this was a pilot study with a limited sample size suggests that there is a need for further research into the physiological demands of batting.

Table II: Physiological responses of cricketers (n=10) taken from the study by Christie et al. (2008) (data are means(\pm SD))

Overs	Heart rate ($\text{bt}\cdot\text{min}^{-1}$)	Breathing frequency ($\text{br}\cdot\text{min}^{-1}$)	Tidal volume (l)	Minute ventilation ($\text{l}\cdot\text{min}^{-1}$)	Oxygen uptake ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	Respiratory exchange ratio
1	126 (14.10)	26.15 (2.55)	1.90 (0.32)	48.47 (5.92)	23.5 (2.90)	0.94 (0.08)
2	135 (16.80)	28.94 (3.07)	2.24 (0.30)	62.69 (5.37)	27.0 (3.10)	1.09 (0.05)
3	145 (19.90)	29.89 (3.31)	2.25 (0.30)	65.87 (7.09)	27.3 (3.50)	1.09 (0.06)
4	149 (19.00)	31.64 (2.77)	2.22 (0.26)	68.53 (4.67)	27.4 (2.50)	1.08 (0.04)
5	151 (18.60)	32.35 (3.65)	2.17 (0.29)	68.51 (4.87)	27.0 (2.30)	1.06 (0.04)
6	154 (18.70)	33.74 (4.88)	2.16 (0.32)	70.66 (6.39)	27.5 (1.90)	1.04 (0.03)
7	155 (18.40)	35.33 (5.12)	2.09 (0.28)	70.87 (5.22)	27.4 (2.10)	1.03 (0.03)
Mean	145 (10.80)	31.15 (3.09)	2.15 (0.12)	65.08 (7.86)	26.7 (1.40)	1.05 (0.05)

More recently, heart rate responses have been recorded during competitive Twenty/20 and 50 over matches. Nicholson *et al.* (2009) recorded heart rate responses between 149 and 167 $\text{bt}\cdot\text{min}^{-1}$ during Twenty/20 matches and between 139 and 154 $\text{bt}\cdot\text{min}^{-1}$ during 50 over matches. Petersen *et al.* (2010) showed mean heart rate responses of 149 and 144 $\text{bt}\cdot\text{min}^{-1}$ for Twenty/20 and 50 over matches respectively. The fact that these findings were very similar to those of King (2002) and Christie *et al.* (2008) showed the reliability of the values obtained in those laboratory-based protocols.

An extension of the study by Christie *et al.* (2008) sought to quantify the physiological and perceptual demands of performing repeated single shuttle sprints between the wickets during batting (Pote and Christie, in press). The protocol used was designed to mimic the demands of a high scoring ODI and the work-bout was developed based on time-motion analyses of seven high scoring ODIs (260 runs or more) during the 2010 calendar. Teams that were observed included major cricket-playing nations such as England, Australia, West Indies, India and New Zealand. Indian Premier League games were also observed, however data were found to be similar to those of high scoring ODIs, so all data were pooled (Pote and Christie, in press). Pote and Christie (in press) therefore used a slightly adapted protocol from the one used by Christie *et al.* (2008) and King (2002), in that batsmen were required to run six single shuttles an over instead of two double shuttles an over (4 runs). There was also a longer break between balls (35s) and overs (75s). Players were thus required to face 7 overs and run a single every ball in order to simulate the work rate of a high-scoring ODI.

The results from the Pote and Christie study (in press) showed that heart rate, oxygen uptake and energy expenditure increased significantly over time (Table III). The responses were also elevated compared to the studies performed by Christie *et al.* (2008) and King (2002), however this was to be expected due to the differences in the work-bouts. Heart rate responses were very similar to the demands of a Twenty/20 match, indicating that the ODI format of the game may be evolving (Pote and Christie, in press).

Table III: Physiological responses of players (n=12) during the study performed by Pote and Christie (in press) (data are means (\pm SD))

	Over 1	Over 2	Over 3	Over 4	Over 5	Over 6	Over 7
Heart rate (bt.min⁻¹)	* 142 (11.66)	# 152 (12.67)	161 (10.30)	162 (11.05)	164 (11.88)	168 (10.27)	167 (11.93)
VO₂ (ml. kg⁻¹ 1.min⁻¹)	* 24.94 (3.29)	27.27 (4.14)	28.01 (3.94)	27.14 (3.90)	27.17 (4.33)	27.08 (4.13)	26.88 (3.70)
EE (kcal.min⁻¹)	* 9.69 (1.20)	11.08 (1.46)	11.57 (1.40)	11.33 (1.57)	11.29 (1.69)	11.24 (1.48)	11.21 (1.54)

Where: * represents a significant difference ($p < 0.01$) between over one and overs two-seven

Where: # represents a significant difference ($p < 0.01$) between over two and overs one and overs three-seven.

An interesting finding was that the mean energy expenditure of this study was only 240.14 kJ higher than in the Christie *et al.* (2008) study, whose protocol had 14 fewer runs in total (Pote and Christie, in press). Furthermore, it was determined that sprinting one single 42 times resulted in an energy expenditure of 66 kJ per run, whereas running 14 double sprints required an energy expenditure of 98 kJ per run, indicating that the deceleration, turning at the popping-crease and re-acceleration resulted in an additional 32 kJ per run (Pote and Christie, in press). The fact that this did not affect heart rate responses suggests that when the second run is initiated, there is an increase in muscle recruitment and force-producing capabilities (Pote and Christie, in press).

These studies all showed that the physiological demands placed on batsmen are much higher than originally thought. The problem though is that these studies used short duration, high intensity work-bouts and responses were not observed over longer time periods.

The latest study on the physiological demands of batting was performed by Houghton *et al.* (2011a). Movement patterns and physical strain were studied using a simulated batting innings (BATEX[®]) that was developed by these authors in order to replicate the physical demands of scoring a century during an ODI. The fact that

batsmen were performing a protocol that was simulated to represent an ODI century meant that the work-bout was not of a short duration or performed at high intensities, but rather responses were looked at over extended periods of time and at variable intensities. Nine club cricketers from Australia performed the simulated work-bout in an outdoor environment and the physiological responses recorded included heart rate, tympanic temperature and sweat rate. Results showed that heart rate reached a mean of $130 \text{ bt}\cdot\text{min}^{-1}$ and tympanic temperature, a mean of $35.90 \text{ }^\circ\text{C}$; and a $0.30 \text{ }^\circ\text{C}$ increase across the 30 overs of the simulation (Houghton *et al.*, 2011a). Sweat rate was estimated at $0.9 (\pm 0.2) \text{ L}\cdot\text{h}^{-1}$. A limitation of this study was that the physiological measures were delimited to heart rate responses, tympanic temperature and sweat rate. The reliability of these measures has been questioned as it is well known that heart rate is affected by factors other than the work-bout such as food intake, emotional state and medications (Christie *et al.*, 2008), to name a few. In addition the reliability of tympanic measures reflecting core temperature has been questioned (Leong Lim *et al.*, 2008) and sweat rate is also affected by factors such as the testing environment. There is thus a need for a more detailed physiological assessment of batsmen's responses to a protocol like the BATEX[®] one to get a more accurate indication of physiological cost.

RATINGS OF PERCEIVED EXERTION DURING BATTING

Ratings of perceived exertion (RPE) are subjective perceptions of effort during exercise and have been linked to physiological responses (Cafarelli, 1982). Originally it was thought that RPE rises in response to an increase in exercise intensity (Borg, 1970), but recently it has been suggested that it also rises as a linear function of exercise duration (Noakes, 2011). Furthermore, it has also been proposed that RPE is used by the brain to regulate exercise performance when the end-point of a work-bout is known (Tucker, 2009; Noakes 2011). However, RPE during cricket activity has been under researched, especially in terms of batting for extended times.

Research conducted in our laboratory, using the seven over, high intensity spell, showed an increase in batsmen's RPE over time from approximately '10' at the start of the protocol (over one), to approximately '15' at the end of the work-bout (King,

2002). Further research in our laboratory, using a similar work-bout to the King (2002) study also showed an increase in RPE over time from '12', during over one, to '18' during over seven (Sheppard and Christie, in preparation). This was higher than the King (2002) study as participants were required to sprint a 2 every ball compared to two 2s an over (28 runs compared to 84 runs). Pote and Christie (in press) also measured RPE over a seven over period where batsmen were required to sprint a single every delivery (42 runs). Responses were similar to the Sheppard and Christie (in preparation) and increased from over one (10) to over seven (16).

To the author's knowledge, only one study has investigated RPE over extended periods of time. Houghton *et al.* (2011a) measured RPE of batsmen batting for thirty overs (six, five over stages) scoring a simulated ODI century (BATEX[®] protocol). A mean RPE of '13' was recorded and responses increased and decreased with the low and high intensity stages respectively. Stage one elicited the lowest (10) and stage six the highest (16) responses. This was similar to the previous studies in our laboratory probably indicating that players regulate themselves based on a maximal, tolerable RPE (Tucker, 2009).

BATTING PERFORMANCE

Batting in cricket is usually regarded as a mechanical concern, and traditionally coaches have concentrated primarily on improving a batsman's technique with respect to the execution of various strokes (McKellar and Nurick, 1998). Batsmen spend many hours practicing the correct technique to ensure that the ball is hit optimally every time (Stretch *et al.*, 2004).

According to Stretch *et al.* (2002), successful batting in cricket depends largely on the batsman's ability to analyse cues from the bowler's run-up and delivery, as well as information regarding the flight of the ball to anticipate the line, length and speed of the delivery. From this information, which needs to be analysed in 439 milliseconds if a ball is bowled at $40.2 \text{ m}\cdot\text{s}^{-1}$, the batsman must successfully execute a stroke (Stretch *et al.*, 2002). Perhaps therefore, the most important factor for success in batting performance is the ability to watch the ball throughout its flight-path, assess its line and length and then execute a shot or stroke based on this

visual information (McKellar and Nurick, 1998). This is not always the easiest accomplishment to achieve though, as many fast bowlers are able to extract late swing in the air or get the ball to deviate off the surface of the pitch (Stretch *et al.*, 1999). If the bowler can get the ball to deviate laterally during the latter part of its flight path, the batsman is forced to re-assess the stroke to be played (Stretch *et al.*, 1999). The practicing of this technique however, has often been neglected due to a number of circumstances including the difficulty to train this ability (McKellar and Nurick, 1998). The ability to 'pick up' a ball's line and length and to account for any lateral deviation or extra bounce will determine a player's ability to reproduce the accuracy and consistency of the stroke. However, this may be affected by the time the batsman has spent at the crease as well as by a change in the physiological demands placed on the batsman. Stretch *et al.* (2004) looked at the position of impact of a ball striking a cricket bat. Both provincial and club batsmen were used in the study and it was found that there were similar impact points for both these groups. However, it was shown that the provincial batsmen impacted the ball much closer to the mid-line of the bat than did the club cricketers. These results indicated that batsmen with greater skill tend to hit the ball more towards the centre and the inner surface of the bat in order to reduce the risk of being dismissed by an outside edge (Stretch *et al.*, 2004).

Another way in which batting performance can be measured athletically, is to measure the sprint time of the batsman between the wickets. The movement patterns of batsman have recently been documented, and can be used to assess the extent to which the running demands of a simulated batting protocol reflect those of an ODI (Houghton *et al.*, 2011b). According to Houghton *et al.* (2011b), a reliable running-between-the-wickets-performance analysis may be used to better the understanding of fatigue during periods of prolonged batting. Houghton *et al.* (2011b) looked at batting performance in a prolonged simulated innings (BATEX[®] protocol), as well as the reliability and discrimination between playing standards of batsmen. High and low grade district club batsmen were tested and an infra-red timing system was used to sample running-between-the-wickets times. The timing gates were situated 10 m and 5 m from the turning crease, and during a single run sprint time was assessed between these two timing gates. When two, three or four runs were completed, turn time was also assessed. This was the time taken by the

batsman from the 5 m timing gate to the turning crease, and back past the 5 m timing gate. Two trials were completed by the participants as a test-retest design was used to assess the reliability of the performance scores. Results showed that during stages two, four and six, mean sprint times were similar between trials. However turn time was better in stage two than stage 6 (2.29 ± 0.06 s vs. 2.36 ± 0.09 s) in trial one, but was roughly the same during stages two and six (2.31 ± 0.06 s vs. 2.34 ± 0.09 s) in trial two (Houghton *et al.*, 2011b). For stages one, three and five sprint times and turn times were similar between the trials (Houghton *et al.*, 2011b). Furthermore, it was found that during stages two, four and six, the high grade batsmen (3.12 ± 0.11 s) achieved better times than the low grade batsmen (3.17 ± 0.10 s), and the typical error for this variable suggested that the margin in difference was real (Houghton *et al.*, 2011b). The fact that low co-efficients of variation were shown for the performance measure also showed the homogeneity of the sample utilised. From these results it was concluded that running-between-the-wickets-time, turn time and the overall sprint time between the wickets (sum of running-between-the-wickets-time and turn time) were reliable performance indicators of running between the wickets during a prolonged, simulated batting protocol (BATEX[®]). Further, there was a trend for better sprint times in the higher-grade batsmen (Houghton *et al.*, 2011b).

CONCLUSION

Most cricket research has been conducted on bowlers, and there are very limited data available on batsmen and, more specifically physiological responses. Of the research that has been conducted on batsmen, mostly short-duration, high-intensity work-bouts have been used. Although previous literature has shown an increase in the physical demands placed on batsmen during the intermittent periods of a cricket game, it is important to examine the demands over extended periods of time. Furthermore, previous literature has not examined any reliable performance measures, detailed cardio-respiratory assessments, accurate core temperature data and sweat rates over extended batting periods. It is important to understand how these measures impact batting so that intervention strategies can be implemented to improve performance and reduce the risk of injury.

CHAPTER III

METHODS

RESEARCH DESIGN

There is a limited amount of literature examining the physiological responses of batsmen and the studies that have been conducted have typically utilised short duration work-bouts of high intensities, where batsmen have been required to sprint at maximum pace for a limited number of overs (King, 2002; Christie *et al.*, 2008; Pote and Christie, in press). These protocols are thus not representative of a batsman batting for extended periods, such as would be required when scoring a century. Houghton *et al.* (2011a) recently designed the BATEX[®] protocol, which consists of six stages that are representative of scoring a one day international century. This BATEX[®] protocol was used in this research as the independent variable.

The design of this study is a repeated measures design with one condition measuring responses over time (Table IV). The experiment requires players to complete the running requirements of the six stages of the BATEX[®] protocol, during which selected physiological, perceptual and performance responses are recorded.

Table IV: Design matrix

	Stages					
	1	2	3	4	5	6
Condition						

There was a slight modification of the Houghton *et al.* (2011a) protocol, as players were required to 'touch and turn' at the popping crease when running a single instead of 'running through'. This is because energy expenditure is impacted by turning at the popping crease (Pote and Christie, in press), it is more realistic of

actual match-play, and the turning impacts the lower limb musculature (more eccentric contractions of the hamstrings and quadriceps muscles) which is likely to affect physiological cost (Barford and Christie, under review).

DEPENDENT AND INDEPENDENT VARIABLES

The independent variables of the study were the running-between-the-wicket times and bat-ball contact accuracy. The dependent variables of interest included heart rate, oxygen uptake, energy expenditure, breathing responses, respiratory exchange ratio, core temperature and sweat loss (physiological responses), central ratings of perceived exertion (perceptual responses) and accuracy and sprint time between the wickets (performance responses).

CONTROLLED VARIABLES

Hydration and fuelling during the protocol: Players were required to consume an Energade (645 kJ; 39 g CHO's) during the drinks break to avoid hypoglycaemia. This was the only fluid ingested during the protocol.

Temperature: Temperature during testing ranged between 16.00 °C and 28.00 °C with a mean temperature of 20.50 °C.

PLAYERS

The selected sample consisted of 17 male cricketers currently playing for Rhodes University or the country districts cricket. Ethical approval was granted by the Department of Human Kinetics and Ergonomics, Rhodes University, Grahamstown, South Africa's Ethical Standards Committee for research involving human participants (Appendix A). All players were voluntary participants. The players were between the ages of 18 and 27 years and the sample considered only specialist batsmen and not bowlers.

PLAYER SCREENING

Individuals were considered as participants only if there was no history of serious medical illness or serious injury (an injury that could cause the participant any pain or harm). Each player was required to complete a physical activity-screening

questionnaire to determine whether this was the case (Appendix A). Once the screening questionnaire was completed participants were given a written information sheet which provided information about the study and the testing procedures as well as the risks and the potential benefits of the study (Appendix A). The testing procedures were then explained to the players verbally as well as in writing and players were asked to sign a consent form (Appendix A).

EXPERIMENTAL CONDITION

Data used to design the protocol were collated from “CricInfo” and statistics were collected between 2003 and 2009 (Houghton *et al.*, 2011a).

Table V: The six stages (21 minutes each) of the BATEX[®] protocol and the number of runs completed in each over (adapted from Houghton *et al.*, 2011a).

BATEX stage and description	Runs completed in each over of BATEX				
	Over 1	Over 2	Over 3	Over 4	Over 5
1. Building momentum	1,1	No runs	1,1,2	1,4	1,4
2. Taking initiative	1,1	1,1,2	1,1,4	1,1,2	1,1,4
3. Fighting back	No runs	1	1,4	2,3	1,4
4. Power play	1,1,4	1,1,2	1,1,4	1,1,2,3	1,1,4
5. Maintaining tempo	1,3	1,1,2	1,1,4	1,1,2	1,1,4
6. Closing out the innings/game	1,1,3,4	1,1,2,4	1,1,4,1	1,1,2	1,1,2,4
Overall	49 1's	11 2's	4 3's	15 4's	34 turns

The running requirements of the protocol were obtained from analyses of the 2007 and 2009 Twenty/20 world cups, the 2003 and 2007 One Day International world cups, and the home and away Test match series between South Africa and

Australia between 2008 and 2009 (Table V). Overall the batsmen were required to run 49 1's, 11 2's, 4 3's, 15 4's and were required to turn 34 times (Table V). Although the entire protocol was designed to be typical of a ODI century, twenty/20 and test match analyses were used for the design of certain individual stages for training purposes (stages can be used as stand-alone training sessions) (Houghton *et al.*, 2011a). For the ODI analyses, only those games where more than 200 runs were scored were taken into account and the teams under analysis were all major cricket playing nations. The same occurred for the analysis of the test series between South Africa and Australia (greater than 200 runs). The analyses of the twenty/20 matches took into account only those matches where more than 150 and 130 runs were scored (for adequate sample size). The data collected for the ODI matches were collated for the maximum distribution of run frequency, individual innings of batsmen one to four, and when individual 50 to 100 runs were scored, and in the last two situations, the run frequency was doubled to reflect two batsmen batting together (Houghton *et al.*, 2011a). This was done to reflect the different stages of an ODI innings. Overall, the physical workload was designed to reflect the mean run distribution of an ODI (Houghton *et al.*, 2011a).

The protocol consisted of 6 stages (21 minutes, 5 overs each) and took 2 hours and 20 minutes to complete. Each stage was specific to a certain phase of play where batsmen were encouraged to bat with the mindset typical of that phase. There was a 2 minute 30 seconds break between each stage, as well as a 4 minute break at the half way point. There was also a break of 35 seconds between balls and 80 seconds between overs. This was similar to the times observed by Sheppard and Christie (in preparation), where a break of 35 seconds was observed between balls and 75 seconds between each over. During stages 1, 3 and 5 batsmen were required to run at a "self-selected cruise pace" whereas during stages 2, 4 and 6 batsmen were required to sprint at maximum speed. Due to the fact that the players' 'self-selected pace' may differ between individuals, the use of Borg's RPE scale was thoroughly explained to each player before performing the protocol.

A research assistant delivered the balls using a bowling machine and an audio track notified the assistant when to release the next ball. The audio track was also used to notify the batsmen of how many shuttle runs (17.68 m, the length of a cricket pitch) to complete in the upcoming over. For example the batsman may be required to run

1, 1, 4, 1 shuttle runs and may complete the runs in any order, but is encouraged to match the number of runs with the shot played and the fielding settings associated with each stage. Running a '4' was equivalent to running 1.5 runs, which often occurs in a game scenario, when the batsman completes 1.5 runs while the ball is rolling to the boundary. No running was required for a '6' in the BATEX[®] protocol and running 5 or more runs was not included as this occurrence is very rare. Extras were also excluded from the protocol as batting scorecards did not show how these runs were completed. However, the protocol was designed to ensure that the batsmen also ran when they were at the non-strikers end, to simulate the runs scored by the other batsman.

MEASUREMENT PROTOCOL AND INSTRUMENTATION

DEMOGRAPHIC MEASUREMENTS

During the initial testing session each player's general demographic data were obtained. This included age and level of cricket activity. Players were also asked about previous medical conditions and injuries (Appendix A).

ANTHROPOMETRIC AND MORPHOLOGICAL MEASURES

The anthropometric data and morphological characteristics of each participant were obtained during the initial testing session. This comprised stature, mass and percentage body fat. From these data, the body mass index (BMI) of each player was calculated.

Stature

The stature of each player was measured using a calibrated Harpenden Stadiometer (London, United Kingdom), calculated accurate to the nearest millimetre. Players were asked to remove shoes, any form of headgear and were asked to stand in an upright position on the stadiometer facing forward with feet together (heels pressed against the base of the stadiometer) with hands at their side, after which the measurement, taken at the highest point of the player's head, was recorded on the data collection sheet (Appendix B).

Body mass

The body mass of each player was measured using a calibrated LifeMax electronic scale (Johannesburg, South Africa) and the measurement was recorded to the nearest 0.01 kg. Players were required to remove footwear as well as any accessories and heavy clothing such as jackets. Once ready players were required to stand in an upright position in the middle of the scale as still as possible, and body mass was recorded.

Body mass index (BMI)

BMI was calculated using the player's stature and body mass. The following equation was used:

$$\text{Body mass index (BMI)} = \frac{\text{Body mass (kg)}}{\text{Stature}^2 \text{ (m)}}$$

Body fat percentage

The players' body fat percentages (%BF) were obtained using skinfold measures. A Harpenden Skinfold caliper (Sussex, United Kingdom) was used to record seven skinfold sites, namely the chest, triceps, subscapular, suprailliac, abdominal, thigh and axilla. To maintain consistency, all measures were taken on the right hand side of the body. For the measurement, the skin was pinched to raise a double layer of skin and the underlying adipose tissue, but care was taken not to raise any muscle. The skinfold caliper was then placed 10mm below and at right angles to the pinch, halfway between the crest and the base of the anatomical site, and a reading in millimetres was taken. This was performed three times on each anatomical site to reduce the margin of error. The Body density (BD) of each player was calculated using the equation devised by Jackson and Pollock (1978) for males:

$$\text{BD} = 1.11200000 - 0.00043499(\text{sum of 7 skinfolds}) + 0.00000055(\text{sum of 7 skinfolds})^2 - 0.00028826 (\text{age})$$

The body fat percentage of each player was then calculated using the Siri equation:

$$\%BF = (495 / \text{body density}) - 450$$

PHYSIOLOGICAL RESPONSES

Respiratory responses

Respiratory responses were measured using a portable on-line metabolic system known as the k4b² (Cosmed[®], Rome). Responses measured included breathing frequency (Rf), tidal volume (V_T), minute ventilation (V_E), oxygen consumption (VO_2), metabolic carbon dioxide production (VCO_2) and respiratory exchange ratio (RER). From these measures energy expenditure was determined. Before each testing session, the k4b² was calibrated using a Hans Rudolph 5530 3-L syringe for volumetric calibration. After this was complete, the sensors were calibrated using a gas mixture (16.10% Oxygen, 4.90% Carbon Dioxide, and 79.00% Nitrogen) and room air calibration was also performed. Players were connected to the portable k4b² through a suitably sized mask. The mask was fitted to the player in such a way as to ensure that no air escaped through any gaps between mask and face. The portable unit was fitted to the participant's back with a harness and players were habituated (until they felt comfortable) to the equipment before the testing procedure took place.

Heart rate (HR) responses

Heart rate was recorded using a Polar[®] heart rate monitor (Kempele, Finland). The heart rate monitor consisted of a transmitter connected to an electrode strap around the player's chest. The Polar[®] transmitter is compatible with the k4b² metabolic system and responses are sent telemetrically to the unit.

Core temperature (T_c) responses

Core temperature responses were recorded using the CoreTemp[®] (HQInc., United States of America) core body temperature monitoring system. The system consists of an ingestible core body temperature sensor or pill and an ambulatory data recorder. Before the pill was ingested it was activated by removing a magnet attached to it in order to ensure that data were sent to the recorder. Players were required to swallow the sensor with a glass of water 2 hours before performing the protocol. This ensured that the pill was in the digestive tract before any responses were collected. The sensor wirelessly transmitted core body temperature from the

digestive tract of the player and the data recorder picked up the signal from the sensor and converted it into digital format. Core temperature data were recorded to the nearest 0.10 °C, and stored on the recorder for later analysis. Responses were collected after each over and after each stage of the BATEX[®] protocol.

Sweat loss and sweat rate

The total water loss during the protocol was calculated by observing changes in body mass (BM). Players were weighed before the start of the work-bout and on completion of the protocol. A Toledo[®] electronic scale was used to calculate the changes in body mass and measurements were recorded to the nearest 0.01kg. All players were weighed without full cricket kit to ensure that any sweat that had accumulated within the kit during the protocol, did not affect the reliability of the measurements obtained.

A density of 1.00g.ml⁻¹ was assigned to water, and Absolute Sweat Loss (SL_{ABS}) was estimated using the equation:

$$SL_{ABS} (L) = [BM \text{ before protocol (kg)} - BM \text{ after protocol (kg)}] \times g.ml^{-1}$$

Relative Sweat Loss was estimated using the equation:

$$SL_{REL} (\% BM) = [SL_{ABS} (L) / BM \text{ before protocol (kg)}] \times 100kg.L^{-1}$$

Note: 1kg = 1L

The Absolute Rate of Sweat Loss (SR_{ABS}) was calculated by dividing the absolute quantity lost by the duration of the activity in minutes and then multiplying this figure by 60 minutes to gain a value in L.h⁻¹:

$$SR_{ABS} (L.h^{-1}) = [SL_{ABS} (L) / \text{duration of protocol (min)}] \times 60min.h^{-1}$$

The Relative Rate of Sweat Loss (SR_{REL}) was calculated by dividing relative sweat loss by the duration of the physical activity and multiplying this value by 60 minutes:

$$SR_{REL} (\% BM.h^{-1}) = [SL_{REL} (\% BM) / \text{duration of protocol (min)}] \times 60min.h^{-1}$$

PERCEPTUAL RESPONSES

Ratings of Perceived Exertion (RPE)

The players' perceived physical effort was rated using Borg's (1998) rating scale (Appendix B). The Borg scale is a graded rating scale that ranges from a minimum rating of 6 or "very, very light" to a maximum rating of 20 or "very, very hard". For this study only central ratings of perceived exertion were recorded which focused on the strain placed on the cardio-respiratory system. Prior to testing the recruits were familiarised with the Borg scale. During the testing procedure, participants were required to rate their central RPE to determine their level of perceived exertion. This rating took place after every over (after every six balls) as well as after every stage of the BATEX[®] protocol, during the periods of inactivity.

PERFORMANCE PARAMETERS

The performance measures assessed during the investigation included sprint time between the wickets (during the stages of maximal intensity sprinting) and the accuracy of the impact of the ball on the bat.

Sprint time between wickets

Sprint time between the wickets was assessed using a system that has been used in previous cricket studies in our department (King, 2002; Sheppard and Christie, in preparation). The sprint timer system consists of LED sensors (switches) as well as a timing device and was developed by the Department of Human Kinetics and Ergonomics, Rhodes University, Grahamstown, South Africa (Figure 2).

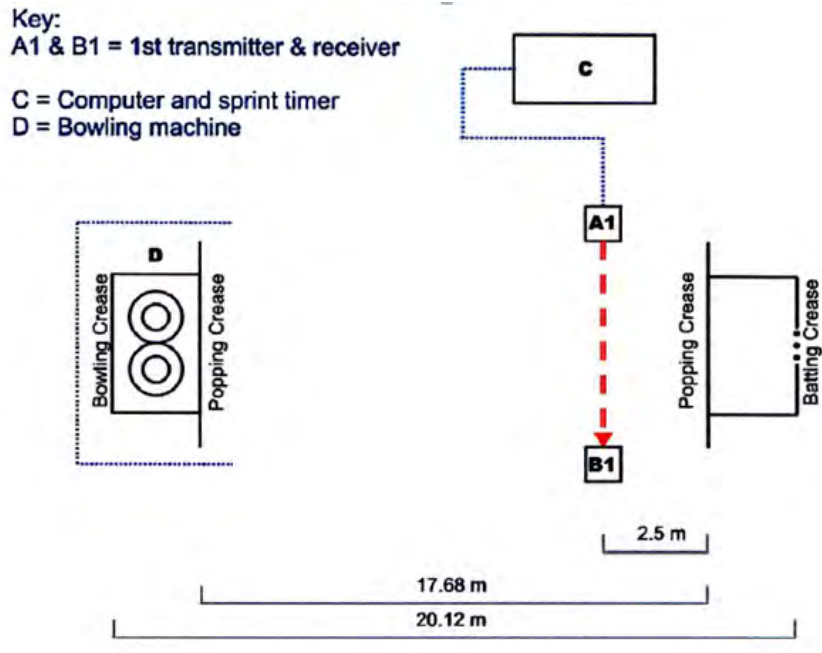


Figure 2: Diagram showing the placement of the LED transmitters and receivers as well as the timing device

The switches were mounted on steel poles at a height of 1.2m and were placed at the striker's end of the wicket, 2.5m from the popping crease. Each switch consisted of an LED transmitter and receiver and these were placed opposite each other across the width of the pitch. The switches were then connected to a timing device. The batsmen would have to pass through a set of sensors (at the batting end) when starting to sprint and again on return to the striker's end. Each time the batsman passed between the sensors, the signal was broken between the transmitter and the receiver, and this triggered the timing switches which in turn measured the batsman's sprint time between the wickets. This was measured only during stages two, four and six of the protocol, when the batsmen were required to perform maximal intensity sprints. Only the double singles (2 runs) that were sprinted during stages two, four and six were recorded in order to obtain reliable and accurate times. These times were then compared between the stages to determine whether there was a change in the batsmen's sprint time between the wickets during the protocol.

Accuracy

Accuracy was assessed using a short handle bat (weight: 1.46 kg) fitted with specialised wireless electronic equipment which detected the impact site of the ball on the face of the bat. The impact site was detected using a pair of flexible circuit boards. These circuit boards were etched in order to produce a switch matrix on the face of the bat so that when the ball hit the face, the two flexible foils were forced together and this produced a contact point (Figure 3). This contact point was registered on X and Y co-ordinates on the switch matrix, and the information was then sent from a micro-controller on the bat to a USB module plugged into the computer, where the X and Y co-ordinate registered on the screen (Figure 4). The data were then copied into an Excel spreadsheet where, using basic trigonometry, the impact site of the ball could be calculated (displacement in mm) relative to the 'sweet spot' of the bat. According to McKellar and Nurick (1998), the 'sweet spot' is situated 160 mm from the base of the bat and in the centre across the width. For this study these same measurements were used.

For example, if the ball impacted on the 'sweet spot', the X;Y co-ordinate registered 0;0 meaning that the distance from the sweet spot to the point of impact was 0 mm. If the ball impacted on the edge of the bat, the X;Y co-ordinate may have been the maximum reading of +3;+10 meaning that the ball impacted 125.72 mm from the 'sweet spot'. When the players missed the ball completely, the maximum X;Y co-ordinate was assigned (+3;+10). In order to protect the circuit boards from any impact damage, the face of the bat was covered in foam and tape (Figure 5). To further protect the bat, the accuracy measure was only recorded during the first over of each stage and for the remaining overs the players used their own bats.



Flexible circuit boards

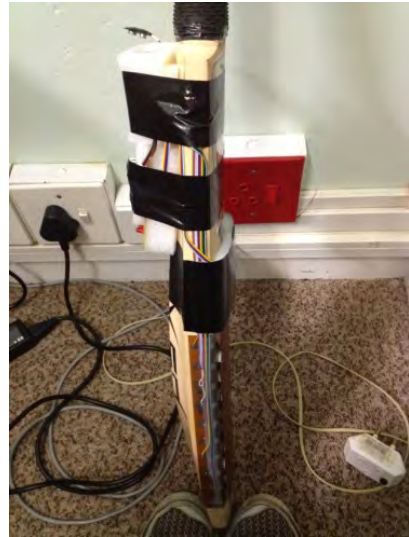


Figure 3: Front and side view of the cricket bat showing the circuit boards that produce a contact point (X;Y co-ordinate) when forced together by the impact of the ball.



Micro - controller

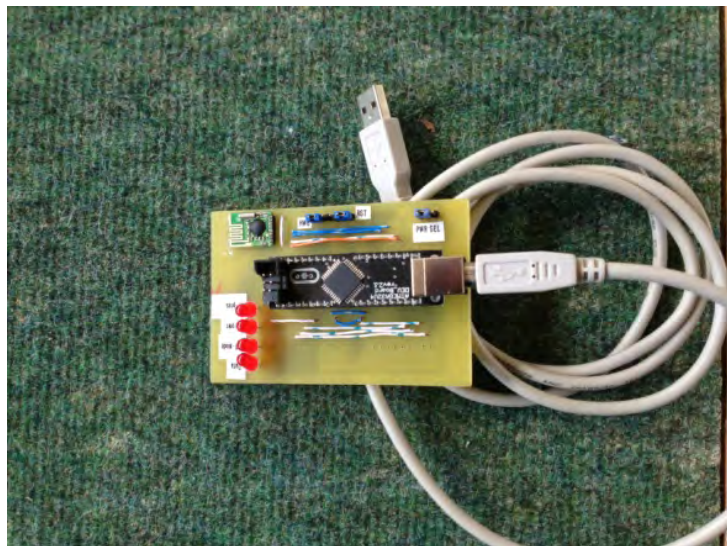


Figure 4: Micro-controller (left) and USB module (right) used to send and receive the X;Y co-ordinates.



Figure 5: Front and side view of the completed bat with protective foam and tape.

PILOT TESTING

Prior to testing, several pilot studies were conducted. This was to ensure that the work-bout used for the study was appropriate for the test objectives, and to determine whether the equipment (k4b², CoreTemp[®] core body temperature monitoring system, accuracy measure on the bat and sprint time equipment) and rating scales (RPE rating scale) were suitable for the dynamic nature of the protocol. Through pilot testing it was deemed necessary to control the speed at which the ball was delivered, to protect the sensors on the bat. It was decided that each ball should be delivered at approximately 105.00 km.h⁻¹ thus allowing the bat to take the impact of the ball for extended periods without doing damage to the sensors.

EXPERIMENTAL PROCEDURES

Two testing sessions were required. The first testing session was used to collect basic anthropometric and demographic data and baseline values. Basic information about the protocol, equipment and test objectives were also explained to the players during this session. During the second testing session (experimental session), the players were required to complete the protocol and physiological, performance and

perceptual responses were measured. The first testing session was carried out at the Department of Human Kinetics and Ergonomics, Grahamstown, South Africa and the second session took place at the High Performance Centre at Kingswood College, Grahamstown, South Africa (Figure 6). Testing also took place in the winter season immediately after the completion of the cricket season, meaning that players were still well trained but well rested, therefore reducing the risk of injury. Training status was however not quantified and is a limitation of the study.



Figure 6: Performing the BATEX[®] protocol in the indoor nets at the Kingswood College High Performance Centre.

TESTING SESSION 1: COLLECTION OF BASELINE DATA

During the first testing session the protocol was explained to the players both verbally and in writing (Appendix A). The objectives of the research project were also explained and this included information regarding the test protocol and procedures. During this session, players were required to fill out and sign a player consent form (Appendix A) and also to complete a physical activity screening questionnaire (Appendix A) to determine whether there were any serious underlying

medical conditions or injuries. The players were then habituated to the equipment and to the BATEX[®] protocol to ensure that all players were comfortable wearing the equipment and performing the protocol. Players were also familiarised with the bat to be used during the first stage of each protocol. Basic anthropometric and demographic data were then collected for each player, which included age, stature, mass and level of cricket activity. Following this, players removed their shirts and a skinfold caliper was used to measure the seven skinfold sites on the right hand side of the body. Players were also instructed as follows: to not consume alcohol 24 hours prior to testing; to not perform any strenuous exercise before testing; to consume a light meal at least an hour before testing and to bring full cricket kit to the experimental and control condition. The type of meal was not controlled and players were requested to eat what they normally eat prior to a cricket game. The nature of this meal was not recorded and so how this pre-exercise dietary composition impacted responses could not be established. The experimenter provided a bat for each player to use due to the nature of the accuracy measure which needed to be controlled. Before the end of the session each player was given a core body temperature pill to ingest and they were reminded that the pill needed to be swallowed with a large glass of water two hours before testing, to allow it to enter the digestive tract. Text messages were sent to participants two hours prior to remind them.

TESTING SESSION 2: EXPERIMENTAL SESSION

Before any testing was carried out players were randomly assigned a testing time to ensure that the data were not compromised, and each player was tested individually. This was also because some players could only be tested in the afternoon and others in the morning. On arrival at the sports centre players performed a warm-up (Appendix A). This was to minimise the risk of injury during the protocol.



Figure 7: Anterior and posterior view of equipment.

Once the warm-up had been completed players were required to pad-up in full cricket kit and were fitted with the portable on-line metabolic system known as the k4b² (Cosmed[®], Rome), which had been calibrated prior to fitment (Figure 7). The data recorder from the CoreTemp[®] monitoring system was then used to determine whether a signal was being sent from the pill in the player's digestive tract. Once it was established that a signal was being sent, each player was required to complete the simulated batting protocol.

Balls were delivered by a research assistant from a bowling machine at a speed of 105 km.h⁻¹ on the batsman's front foot on the off side. The line and length of the delivery was not known by the batsmen prior to completing the protocol in order to obtain the most accurate impact sites with the electronic bat. Players were required to complete the 6 stages (5 overs each) of the BATEX[®] protocol with stages 1, 3 and 5 completed at the participant's self-selected pace and stages 2, 4 and 6 completed at an all-out intensity sprint, typical of a ODI century. At the end of each over and at the end of each stage physiological, performance and perceptual responses were measured and recorded on a data collection sheet (Appendix B). The players' sprint times between the wickets were recorded only during stages 2, 4 and 6 of the protocol when an all-out maximum intensity sprint was required and when a double

run (two) was completed. Players were also required to match the number of runs with the shot played and the field settings associated with the specific stage in order to make the simulated protocol more representative of an actual match. The accuracy of the impact of the ball on the bat was also measured during the protocol and players were encouraged to hit the ball as close to the 'sweet-spot' of the bat as possible. This was only recorded during the first over of each stage. After the experimental session, the equipment was removed from the players and participants were required to take part in a cool-down session, which included a jog and more cricket-specific stretches.

STATISTICAL ANALYSIS

All statistical analyses were performed using STATISTICA (version 10) software. Descriptive measures of physiological, performance and perceptual data included mean values and standard deviations. The level of significance was set at $p < 0.05$, meaning a confidence interval of 95%. The effect size statistic was used to characterise the magnitude of difference between the different stages. The criteria for interpreting effect sizes were: < 0.2 trivial, $0.2-0.6$ small, $0.6-1.2$ moderate, $1.2-2.0$ large and > 2.0 very large (Hopkins, 2004). A one-way analysis of variance was used to compare differences between stages at different intensity levels over time. Post-hoc analyses (Tukey's) were used to identify specific areas of differences.

CHAPTER IV

RESULTS

PLAYER CHARACTERISTICS

Table VI: Basic demographic, anthropometric and morphological characteristics (mean±SD).

	Mean	SD	CV
Age (yrs)	22.47	2.32	10.33
Stature (mm)	1816.10	56.48	3.12
Mass (kg)	81.73	9.96	12.19
BMI (kg.(m²)⁻¹)	24.85	2.77	11.13
Body fat (%)	12.94	2.40	18.56

Where: BMI is body mass index, SD is standard deviation and CV is coefficient of variation (%).

Seventeen batsmen with a mean age of 22.47 years volunteered to participate in the study. The players had similar characteristics except for body fat percentage (Table VI); this varied quite substantially (8.26%-17.54%). Furthermore, a low variance within the standard deviation values (except for body fat percentage) may indicate statistical similarity within the players.

PHYSIOLOGICAL RESPONSES

The mean physiological responses for each stage of the BATEX[®] protocol are presented in Table VII.

Table VII: Mean ((SD) and CV%) physiological responses of batsmen (n=17) during the six stages of the batting protocol.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Mean
HR (bt.min⁻¹)	124 (15.00) 12.09%	148 (15.47) 10.45%	136 (15.67) 11.52%	150 (14.89) 9.93%	144 (15.29) 10.62%	159 (13.52) 8.50%	144 (14.97) 10.40%
Rf (br.min⁻¹)	31 (3) 8.81%	36 (3) 7.35%	35 (3) 9.57%	39 (4) 9.16%	39 (4) 11.53%	42 (4) 9.36%	37 (3) 9.32%
VT (L)	1.51 (0.27) 17.88%	1.75 (0.33) 18.86%	1.40 (0.22) 15.71%	1.79 (0.23) 12.85%	1.40 (0.19) 13.57%	1.73 (0.21) 12.14%	1.60 (0.24) 15.00%
VE (L.min⁻¹)	45.83 (8.39) 18.31%	63.31 (10.99) 17.36%	48.10 (8.65) 17.98%	69.26 (9.30) 13.43%	53.23 (8.44) 15.86%	72.44 (10.08) 13.91%	58.70 (9.31) 15.86%
VO₂ (ml.kg⁻¹.min⁻¹)	29.29 (6.01) 20.52%	38.68 (7.71) 19.93%	31.32 (5.54) 17.69%	41.77 (6.84) 16.36%	35.38 (6.42) 18.15%	43.43 (6.30) 14.51%	36.65 (6.47) 17.65%
VCO₂ (ml.kg⁻¹.min⁻¹)	26.46 (6.06) 22.90%	35.01 (7.04) 20.11%	26.07 (5.43) 20.83%	36.99 (7.27) 19.65%	28.59 (6.67) 23.33%	37.42 (8.16) 21.81%	31.76 (6.77) 21.32%
EE (kcal.min⁻¹)	11.49 (2.04) 17.75%	15.18 (2.63) 17.33%	12.10 (2.11) 17.44%	16.28 (2.23) 13.70%	13.59 (2.51) 18.47%	16.90 (2.53) 14.97%	14.26 (2.34) 16.41%
RER	0.95 (0.19) 20.00%	0.95 (0.18) 18.95%	0.86 (0.16) 18.60%	0.92 (0.19) 20.65%	0.84 (0.17) 20.24%	0.89 (0.18) 20.22%	0.90 (0.18) 20.00%

Where: HR is heart rate; Rf is breathing frequency; VT is tidal volume; VE is minute ventilation; VO₂ is oxygen uptake; VCO₂ is carbon dioxide production; EE is energy expenditure and RER is respiratory exchange ratio. % is coefficient of variation.

Note: White area stages represent the self-selected stages while the grey area stages represent the high intensity stages. Significant and non-significant findings will be shown when each physiological response is represented individually.

HEART RATE (HR)

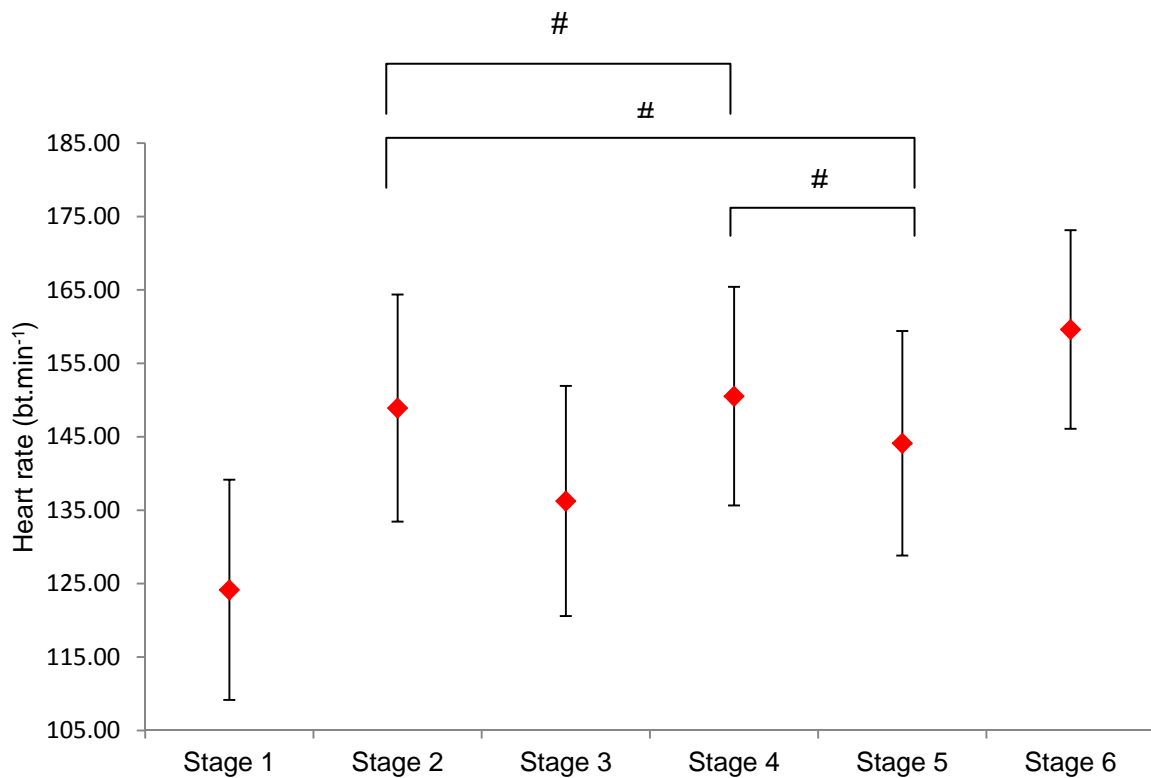


Figure 8: Changes in mean (\pm SD) heart rate responses over time.

Where: # denotes non-significance between stages two and four, two and five and four and five.

Significant changes ($p < 0.05$) were seen in heart rate responses between all stages except between stages two and four, two and five and stages four and five (Figure 8). Throughout the protocol, mean heart rate was $144 (\pm 14)$ bt.min⁻¹ and increased from $124 (\pm 15)$ bt.min⁻¹ (stage one) to the highest response during stage six (159 ± 13 bt.min⁻¹). Mean heart rate during the high intensity stages was $152 (\pm 14.63)$ bt.min⁻¹ which was higher than the self-selected stages of one, three and five (mean of 135 ± 15 bt.min⁻¹).

Table VIII: Effect size and magnitude of heart rate responses.

Stages	Effect size	Magnitude
one-two	1.60	Large
two-three	0.80	Moderate
three-four	0.94	Moderate
four-five	0.40	Small
five-six	1.00	Moderate

Despite these significant findings, the only change of magnitude, with respect to effect size (Table VIII), was between stages one and two (1.60). Thereafter the magnitude of the heart rate change was moderate or small and ranged between 0.40 and 1.00. When the high intensity stages were isolated, the magnitude of the change was also moderate. However, the effect was larger when moving from stages four to six (0.60) than from stages two to four (0.13).

BREATHING FREQUENCY (Rf)

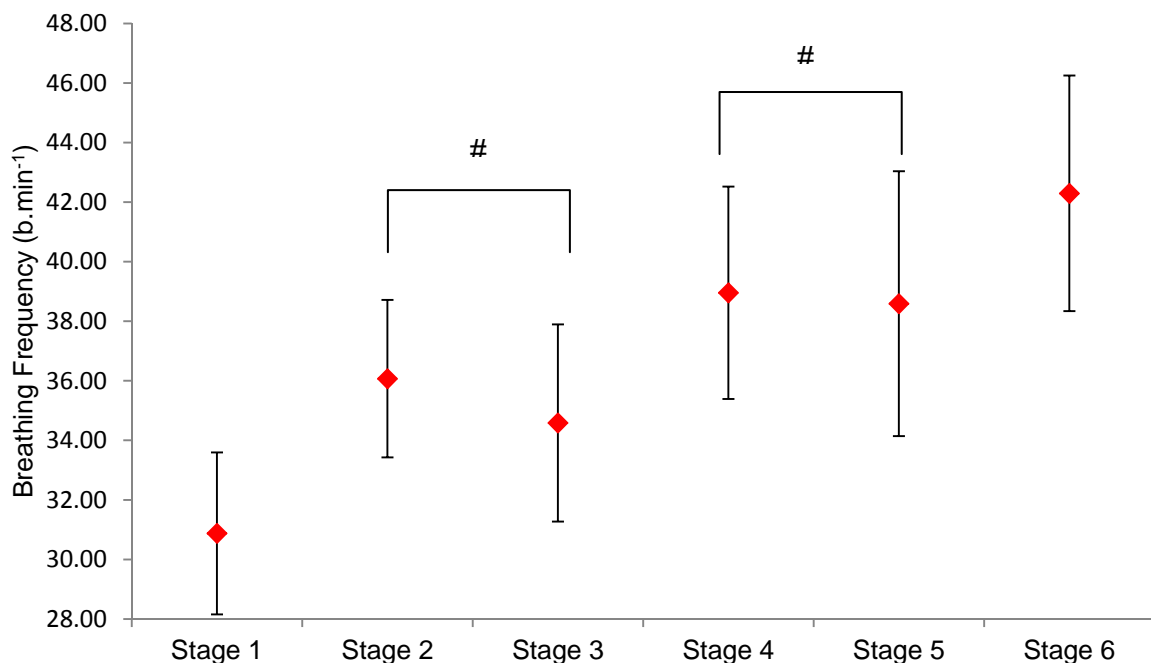


Figure 9: Changes in mean (\pm SD) breathing frequency responses over time.

Where: # denotes non-significance between stages two and three and four and five.

Significant differences ($p < 0.05$) were seen between all stages except between stages two and three and stages four and five for breathing frequency responses (Figure 9). Breathing frequency increased significantly ($p < 0.05$) between stage one (31 ± 2 br.min⁻¹) and the drinks break at the end of stage three (35 ± 3 br.min⁻¹). Responses then continued to rise significantly ($p < 0.05$) between stage four (39 ± 4 br.min⁻¹) and stage six, where a peak response of $42 (\pm 4)$ br.min⁻¹ was recorded. Mean breathing frequency throughout the protocol was $37 (\pm 3)$ br.min⁻¹.

Table IX: Effect size and magnitude of breathing frequency responses.

Stages	Effect size	Magnitude
one-two	1.51	Large
two-three	0.43	Small
three-four	1.27	Large
four-five	0.11	Trivial
five-six	1.08	Moderate

In terms of effect size, the largest change in magnitude was between stages one and two (1.51) and between stages three and four (1.27) (Table IX). The smallest change was seen between stages four and five (0.11). When the high and low intensity stages were looked at separately, the magnitude of the change was only moderate between stages one and three (1.08) and stages three and five (1.17) as well as between stages two and four (0.84) and stages four and six (0.97).

TIDAL VOLUME (VT)

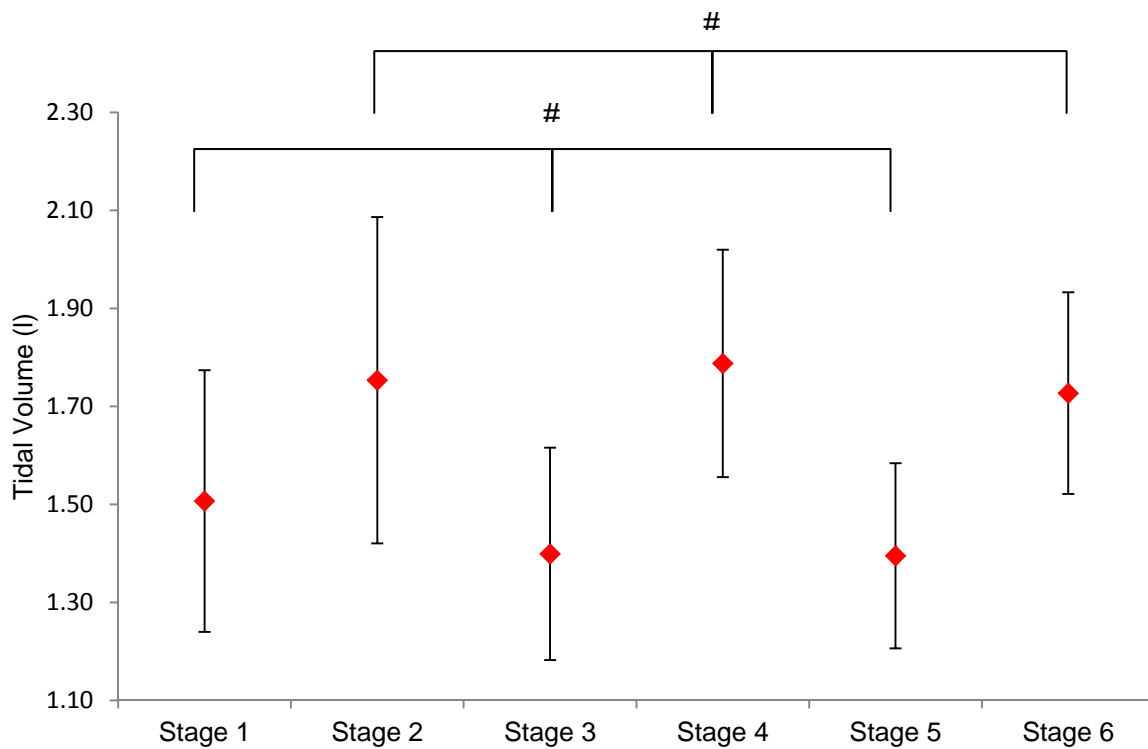


Figure 10: Changes in mean (\pm SD) tidal volume responses over time.

Where: # denotes non-significance between stages one, three and five as well as stages two, four and six.

All tidal volume responses recorded during the low intensity stages (one, three and five) were significantly ($p < 0.05$) lower than the responses recorded in the high intensity stages (two, four and six) (Figure 10). No significant differences were seen between stages one, three and five and between stages two, four and six. Unlike other physiological responses the lowest mean values for tidal volume were recorded during stage three and stage five (1.40 ± 0.22 L and 1.40 ± 0.19 L) while responses peaked after the drinks break, during the high intensity stage four (1.79 ± 0.23 L).

Table X: Effect size and magnitude of tidal volume responses.

Stages	Effect size	Magnitude
one-two	1.00	Moderate
two-three	1.46	Large
three-four	1.63	Large
four-five	1.63	Large
five-six	1.38	Large

The changes in effect sizes were large between all the stages (ranging between 1.2-2.0) except between stages one and two, where a moderate effect size was shown (1.00) (Table X). When effect size was compared during the stages of the same intensity (one, three and five; two four and six) the magnitude of the change was very small.

MINUTE VENTILATION (VE)

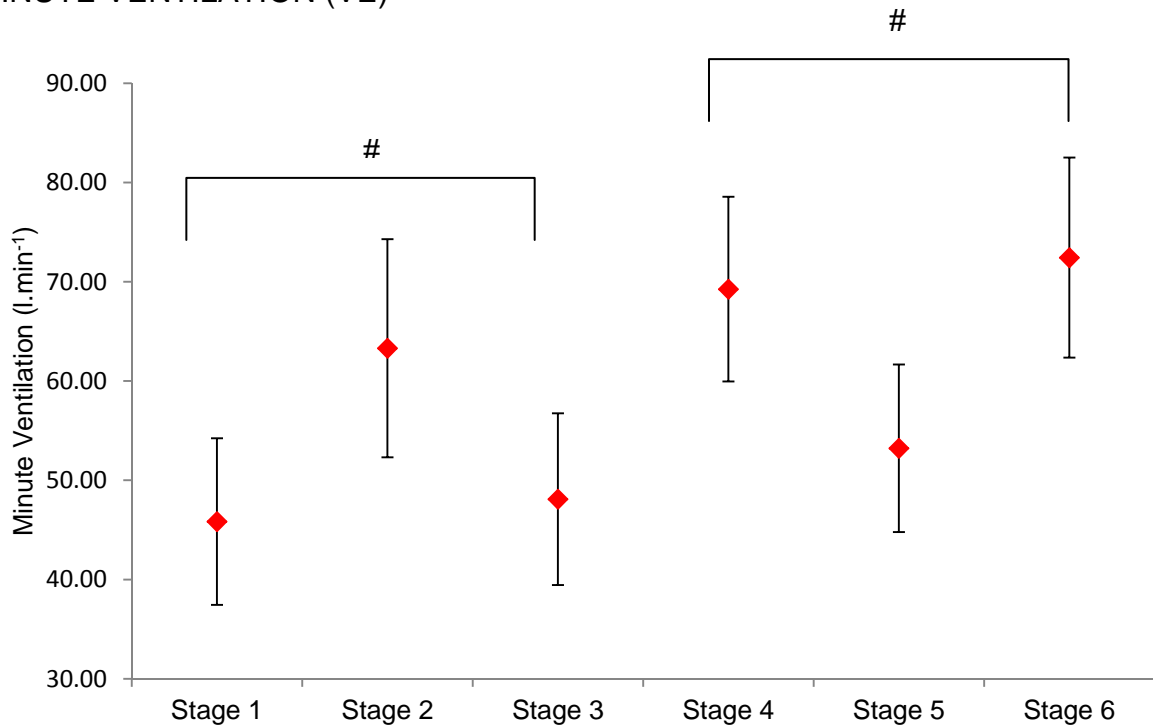


Figure 11: Changes in mean (\pm SD) minute ventilation responses over time.

Where: # denotes non-significance between stages one and three and four and six.

With respect to minute ventilation, significant differences ($p < 0.05$) were seen between all the stages except between stages one and three (both low intensity) and stages four and six (both high intensity) (Figure 11). Like heart rate and VO_2 , minute ventilation responded to the type of stage. The lowest minute ventilation ($45.83 \pm 8.39 \text{ L}\cdot\text{min}^{-1}$) was recorded during the first stage of the protocol and reached a peak of $72.44 (\pm 10.08) \text{ L}\cdot\text{min}^{-1}$ at the end of the protocol (stage 6).

Table XI: Effect size and magnitude of minute ventilation responses.

Stages	Effect size	Magnitude
one-two	1.88	Large
two-three	1.63	Large
three-four	1.12	Moderate
four-five	1.72	Large
five-six	2.06	Very large

A very large effect size (2.06) was shown between stages five and six for minute ventilation (Table XI). The other stages presented large effect sizes (1.88; 1.63; 1.72) except between stages three and four, where a moderate effect size (1.12) was seen. When comparing stages of the same intensity, effect sizes were small, but a moderate effect size (0.64) was seen between the high intensity stages four and six.

OXYGEN UPTAKE (VO₂)

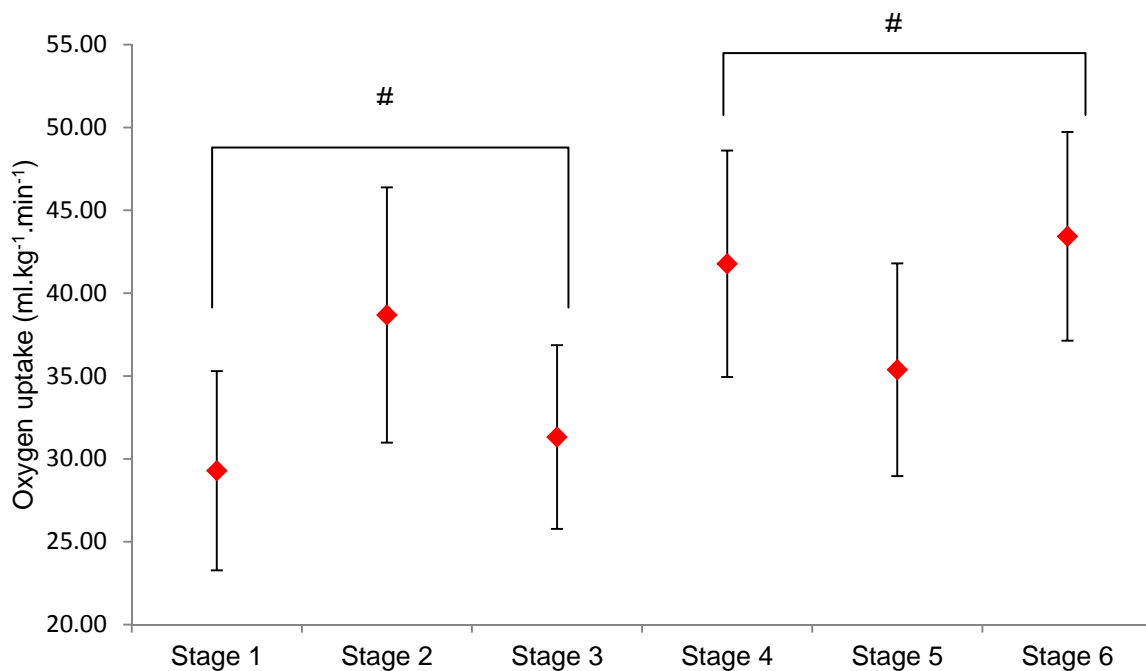


Figure 12: Changes in mean (\pm SD) oxygen uptake responses over time.

Where: # denotes non-significance between stages one and three and four and six.

Significant changes ($p < 0.05$) in oxygen uptake were seen between all stages except between stages one and three and stages four and six (Figure 12). Further, VO₂ followed the same trend as heart rate and increased and decreased in response to the high and low intensity stages respectively. Like heart rate, the lowest mean VO₂ value was recorded during stage one (29.92 ± 6.01 ml.kg⁻¹.min⁻¹), which was a low intensity stage, while the highest mean VO₂ response was recorded during the high intensity, stage six (43.43 ± 6.30 ml.kg⁻¹.min⁻¹).

Table XII: Effect size and magnitude of oxygen uptake responses.

Stages	Effect size	Magnitude
one-two	1.45	Large
two-three	1.14	Moderate
three-four	1.62	Large
four-five	0.99	Moderate
five-six	1.24	Large

Large effect sizes were seen between stages one and two (1.45), stages three and four (1.62) and stages five and six (1.24) for oxygen uptake (Table XII). Only moderate changes were seen between stages two and three (1.14) and stages four and five (0.99). When the high and low intensity stages were isolated, changes were small apart from a moderate change between the low intensity stages three and five (0.63).

CARBON DIOXIDE PRODUCTION (VCO_2)

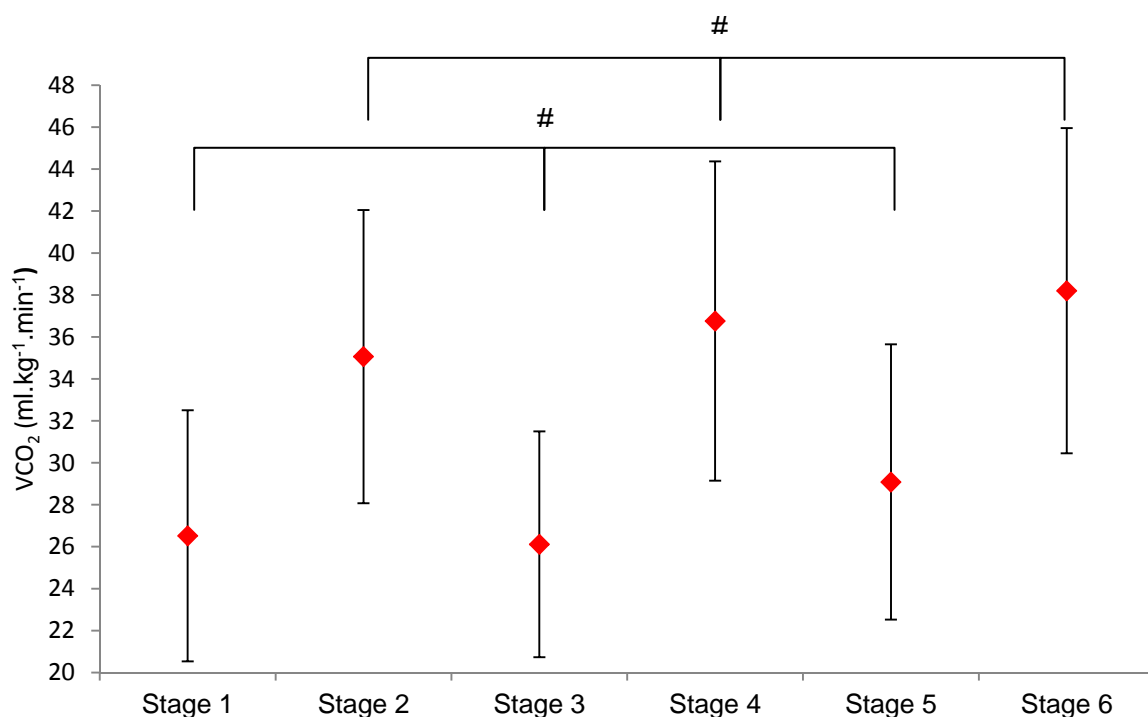


Figure 13: Changes in mean (\pm SD) VCO_2 responses over time.

Where: # denotes non-significance between stages one, three and five as well as stages two, four and six.

Carbon dioxide production responses followed the same trend as tidal volume, and significant changes ($p < 0.05$) were seen between all the stages except between stages one, three and five (low intensity stages) and stages two, four and six (high intensity stages) (Figure 13). Like tidal volume the lowest mean VCO_2 response was recorded just before the drinks break during stage three (26.07 ± 5.43 ml.kg⁻¹.min⁻¹). After this, responses decreased and increased with each low and high intensity

stage respectively, until reaching a peak response of 37.42 (± 8.16) ml.kg⁻¹.min⁻¹ at the end of stage six.

Table XIII: Effect size and magnitude of carbon dioxide production responses.

Stages	Effect size	Magnitude
one-two	1.28	Large
two-three	1.33	Large
three-four	1.63	Large
four-five	1.25	Large
five-six	1.32	Large

Unlike oxygen uptake, carbon dioxide production showed large effects between all the stages (Table XIII). When the high and low intensity stages were compared separately, only small effects were observed.

RESPIRATORY EXCHANGE RATIO (RER)

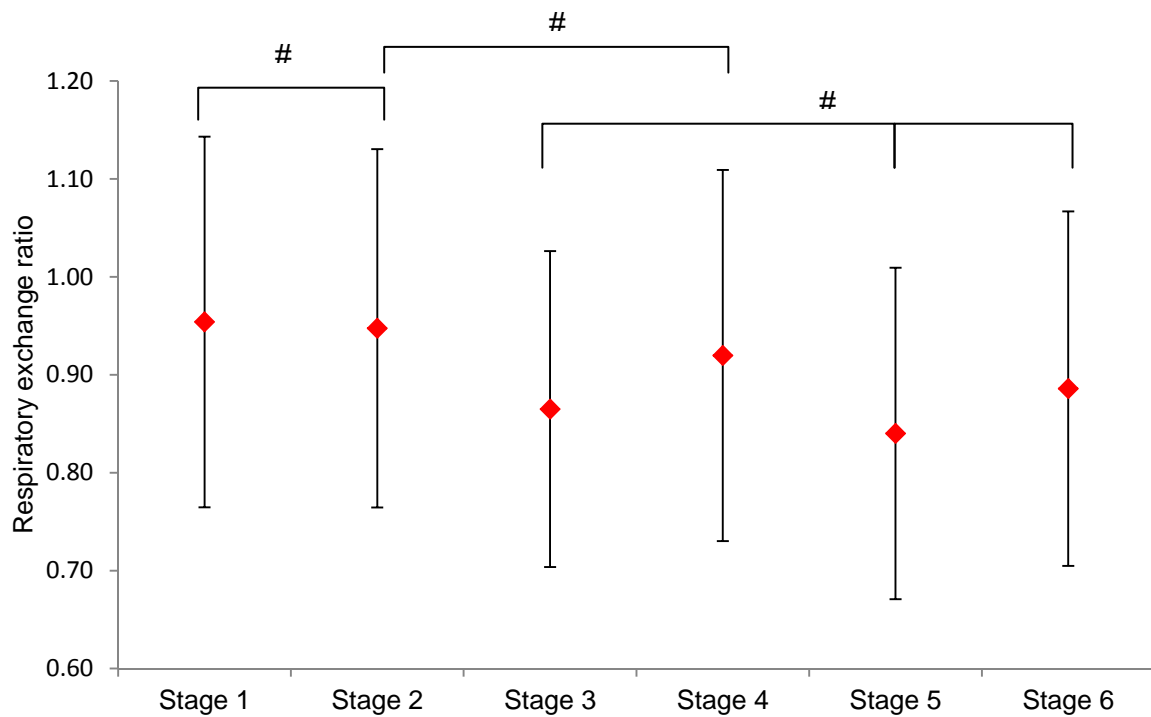


Figure 14: Changes in mean (\pm SD) RER responses over time.

Where: # denotes non-significance between stages one and two, two and four and three, five and six.

For respiratory exchange ratio, significant changes ($p < 0.05$) were seen between all the stages except between stages one and two, stages two and four and stages three, five and six (Figure 14). Unlike the other physiological responses, the highest mean RER value was recorded during stage one (0.95 ± 0.19). Following stage one, RER decreased significantly ($p < 0.05$) until the drinks break (0.92 ± 0.19). After the drinks break, responses increased significantly ($p < 0.05$) (stage four) and then dropped to the lowest mean response (0.84 ± 0.17) during stage five. At the end of stage six RER reached a mean value of $0.89 (\pm 0.37)$.

Table XIV: Effect size and magnitude of respiratory exchange ratio responses.

Stages	Effect size	Magnitude
one-two	0.00	Trivial
two-three	0.50	Small
three-four	0.33	Small
four-five	0.44	Small
five-six	0.27	Small

The magnitude of effect size for respiratory exchange ratio followed the opposite trend from that of carbon dioxide production and only trivial and small magnitude changes were observed between all of the stages (Table XIV). This was also shown when the different intensity stages were compared separately.

ENERGY EXPENDITURE (EE)

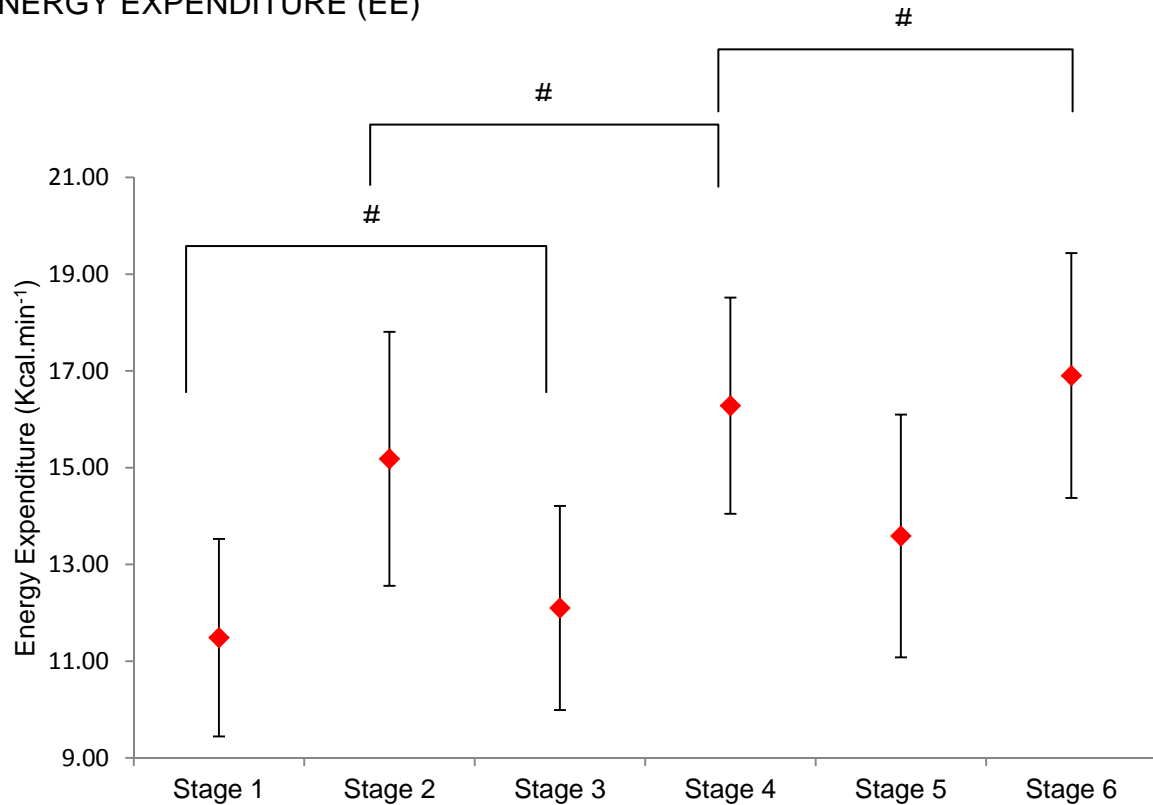


Figure 15: Changes in mean (\pm SD) energy expenditure responses over time.

Where: # denotes non-significance between stages one and three, two and four and four and six.

Significant changes ($p < 0.05$) were shown between all the stages except between stages one and three, stages two and four and between stages four and six for energy expenditure responses (Figure 15). This was expected as stages one and three were low intensity stages while stages two and four and four and six were high intensity stages. There were significant changes ($p < 0.05$) between all of the remaining stages. Energy expenditure followed the same trend as both heart rate and VO_2 and increased during the high intensity stages (two, four and six) and decreased during the low intensity stages (one, three and five). The lowest mean energy expenditure response was recorded during stage one ($11.49 \pm 2.04 \text{ kcal.min}^{-1}$), while the highest mean response was recorded during stage six ($16.90 \pm 2.53 \text{ Kcal.min}^{-1}$).

Table XV: Effect size and magnitude of energy expenditure responses.

Stages	Effect size	Magnitude
one-two	1.58	Large
two-three	1.32	Large
three-four	1.79	Large
four-five	1.15	Moderate
five-six	1.41	Large

For effect size, large magnitude changes were observed between all the stages (1.58; 1.32; 1.79; 1.41) except between stages four and five, where a moderate change was seen (1.15) (Table XV). A moderate effect (0.64) was also shown when the low intensity stages three and five were compared. The remaining high and low intensity stages, when compared separately, exhibited only small magnitude changes.

CORE TEMPERATURE (T_c)

Table XVI: Mean ((SD) and CV%) Core temperature responses recorded during the six stages of the protocol.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Mean
T_c (°C)	37.65 (0.27) 0.72%	38.21 (0.23) 0.60%	38.39 (0.30) 0.78%	38.17 (0.80) 3.00%	38.46 (0.44) 1.14%	38.70 (0.37) 0.96%	38.26 (0.40) 1.05%

Where: T_c is core temperature. % is coefficient of variation.

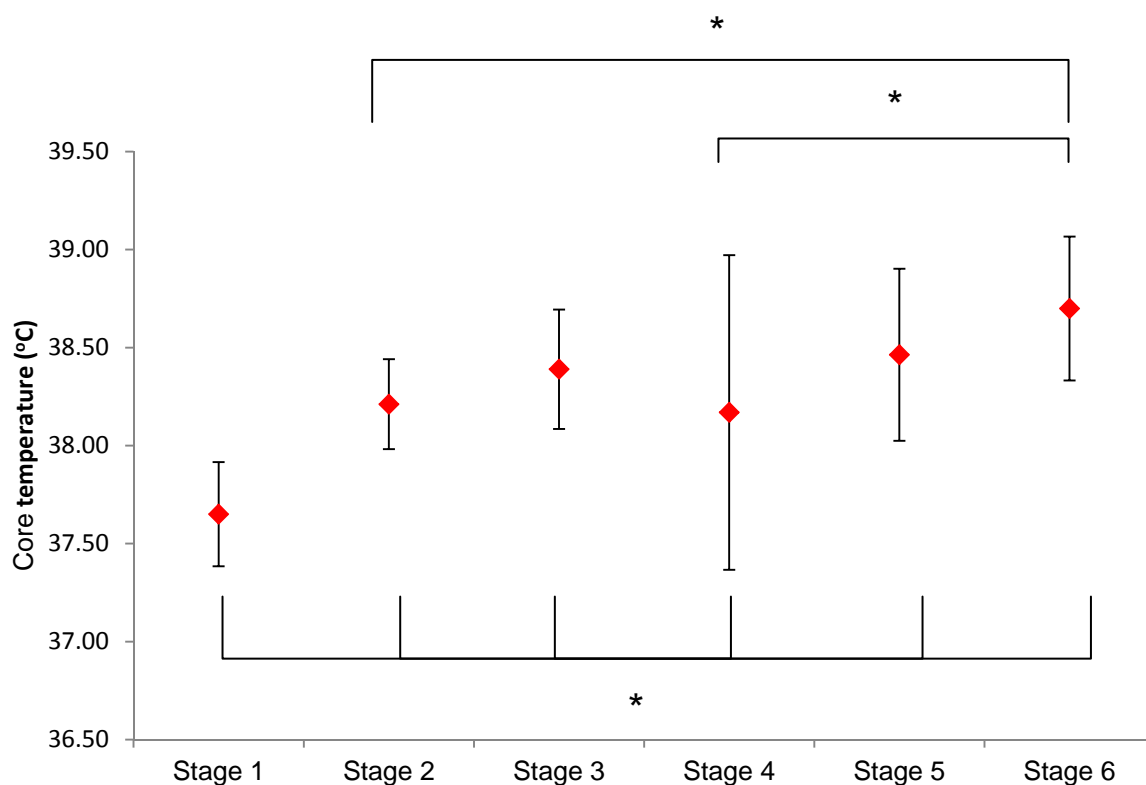


Figure 16: Changes in mean (\pm SD) core temperature responses over time.

Where: * signifies a significant difference between stage one and stages two-six, stage two and six and stage four and six.

Significant changes ($p < 0.05$) were seen for core temperature responses between stage one and stages two-six as well as between stages two and six and stages four and six (Figure 16). Core temperature responses continued to rise from stage one (37.65 ± 0.27 °C) until the drinks break (stage three) where a mean of $38.39 (\pm 0.30)$ °C was recorded. After the drinks break, responses decreased to $38.17 (\pm 0.80)$ °C and then continued to rise until the end of the batting protocol, where a peak of $38.70 (\pm 0.37)$ °C was reached during stage six. Mean core temperature throughout the protocol was $38.26 (\pm 0.40)$ °C.

Table XVII: Effect size and magnitude between the different stages of the protocol.

Stages	Effect size	Magnitude
one-two	1.40	Large
two-three	0.45	Small
three-four	0.55	Small
four-five	0.73	Moderate
five-six	0.60	Moderate

The only large effect (1.40) was observed between stages one and two for core temperature responses (Table XVII). The other changes were either moderate or small. However, when the high and low intensity stages were isolated, large changes were also observed between the low intensity stages one and three (1.85) and the high intensity stages four and six (1.33).

SWEAT LOSS AND SWEAT RATE

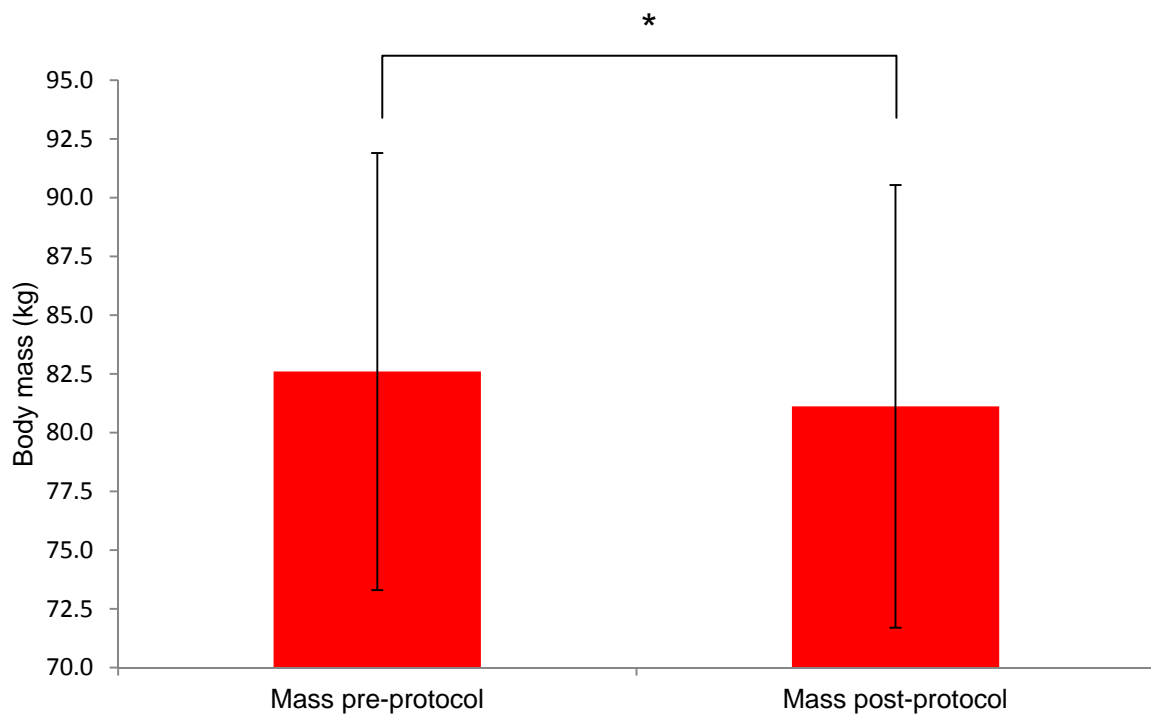


Figure 17: Changes in mean (\pm SD) body mass pre and post the batting protocol.

Where: * signifies a significant difference between body mass before the protocol and body mass after the protocol.

The players' body mass decreased significantly ($p < 0.05$) over time during the batting protocol from 82.60 kg immediately prior to the start of the protocol to 81.12 kg on completion of the protocol (Figure 17).

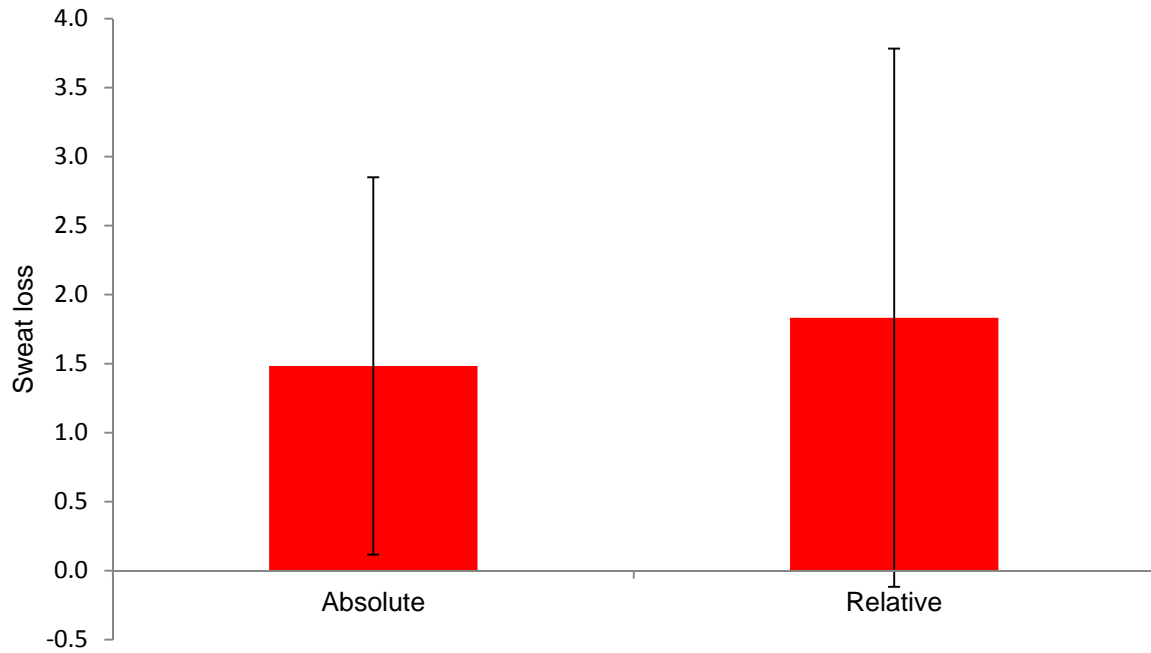


Figure 18: Changes in mean (\pm SD) absolute (L) and relative (%BM) sweat losses.

Mean absolute sweat loss was 1.48 L while relative sweat loss was 1.83% (Figure 18).

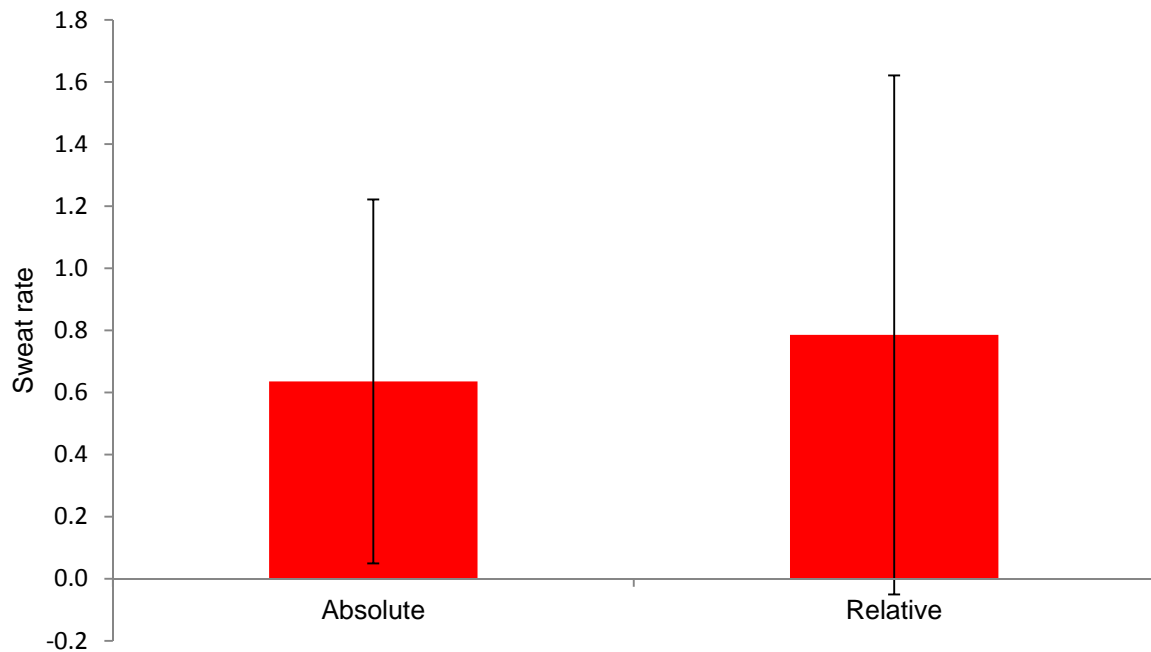


Figure 19: Changes in mean (\pm SD) absolute (L.h⁻¹) and relative (%BM.h⁻¹) sweat rates.

Absolute sweat rate reached was $0.64 \text{ L}\cdot\text{h}^{-1}$ while relative sweat rate was $0.79 \text{ \%BM}\cdot\text{h}^{-1}$ (Figure 19).

PERCEPTUAL RESPONSES

CENTRAL RATINGS OF PERCEIVED EXERTION (RPE)

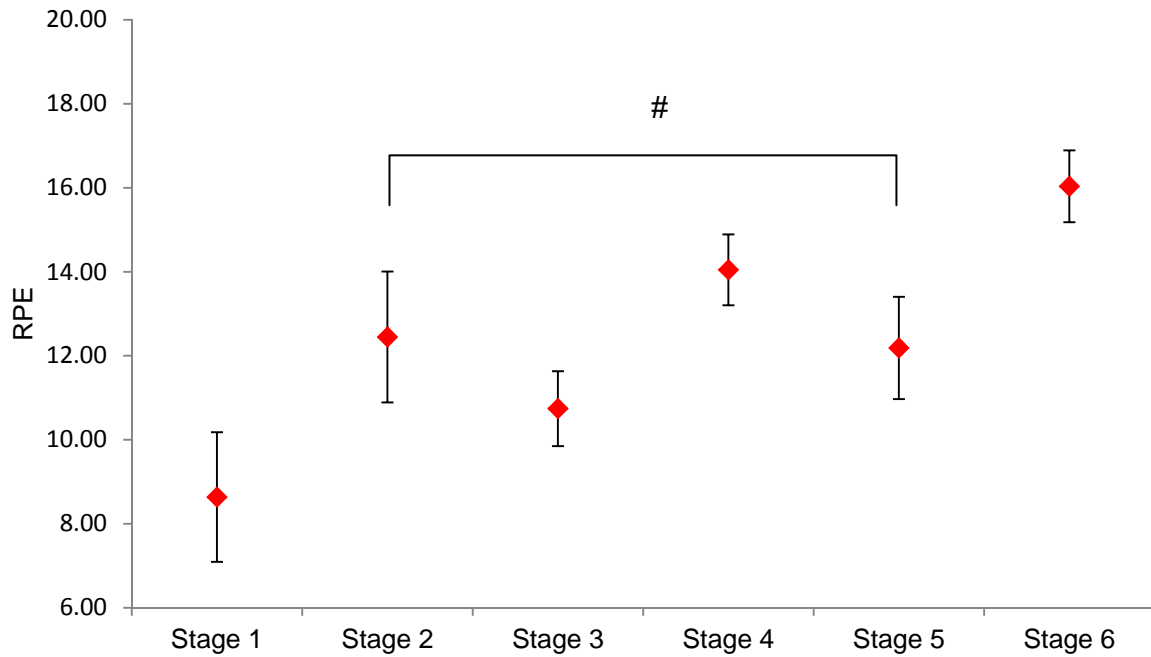


Figure 20: Changes in mean (\pm SD) central ratings of perceived exertion over time.

Where: # denotes non-significance between stages two and five.

Central ratings of perceived exertion increased significantly ($p < 0.05$) over time except between stages two and five (Figure 20). The lowest rating was recorded during stage one of the protocol (8.63 ± 1.54), while the highest rating was recorded during stage six at the end of the protocol (16.04 ± 0.86). Mean RPE for the protocol was 12.35.

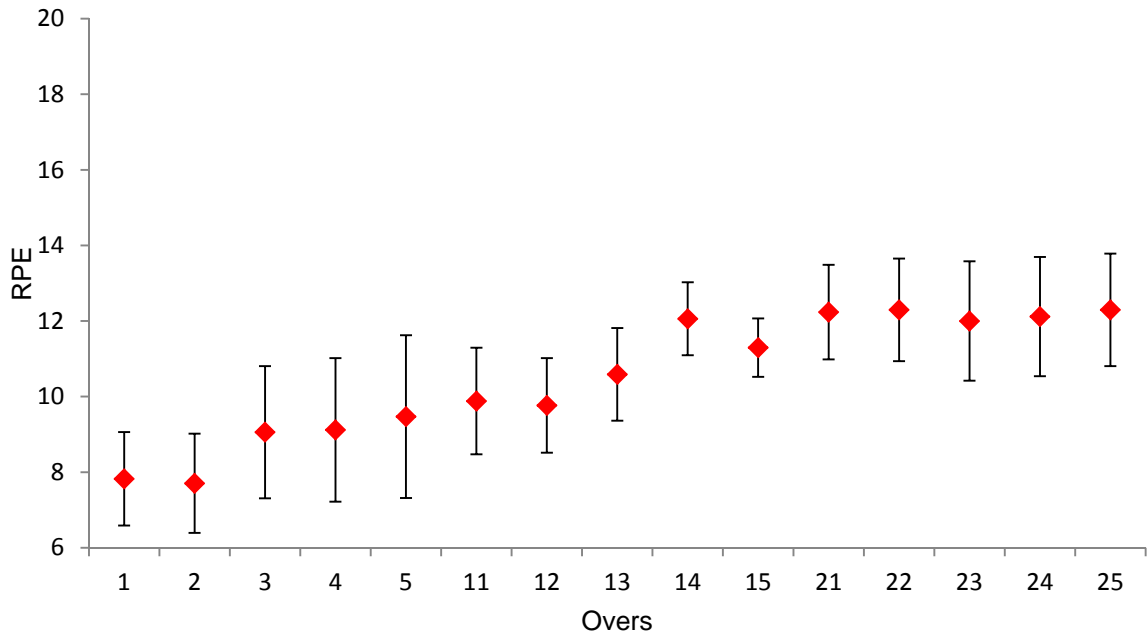


Figure 21: Changes in mean (\pm SD) central ratings of perceived exertion for the low intensity stages.

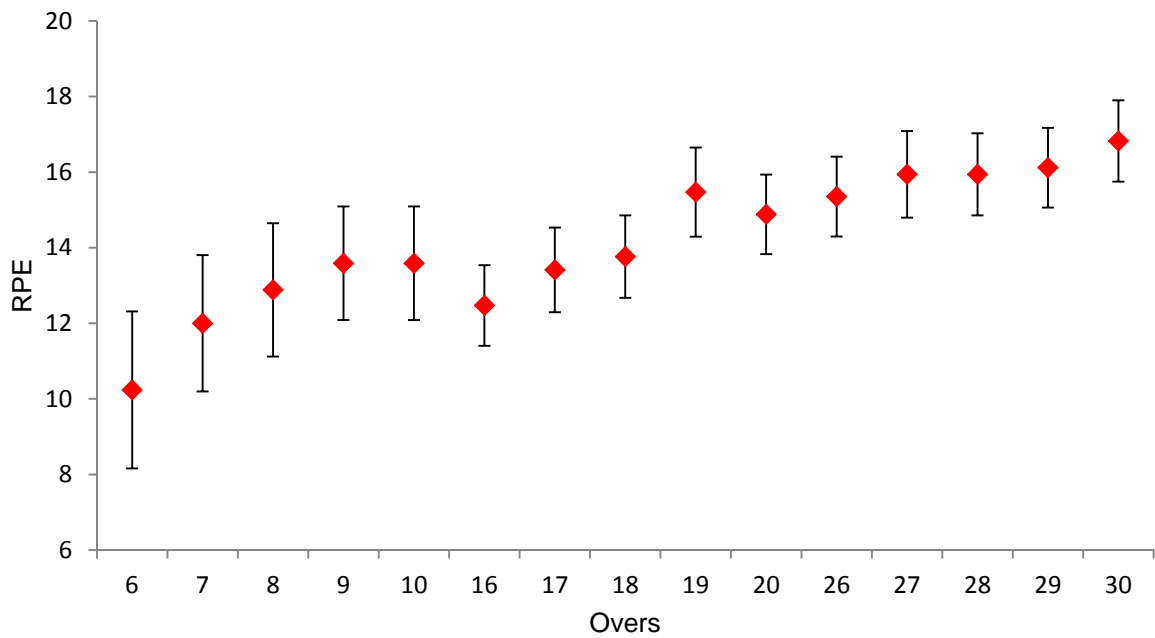


Figure 22: Changes in mean (\pm SD) central ratings of perceived exertion for the high intensity stages.

Figure 21 and 22 show the mean central ratings of perceived exertion when the low and high intensity stages are isolated. For the low intensity stages, over two in the first stage showed the lowest response (7.71) and over twenty two and twenty five in the fifth stage elicited the highest response (12.29). The total rise in RPE throughout the protocol for the low intensity stages was 4.58. In terms of the high intensity stages, the lowest RPE response was recorded during the sixth over in stage two (10.24) and the highest response was recorded during the last over (over thirty) in stage six (16.82). The rise throughout the protocol was therefore 6.58.

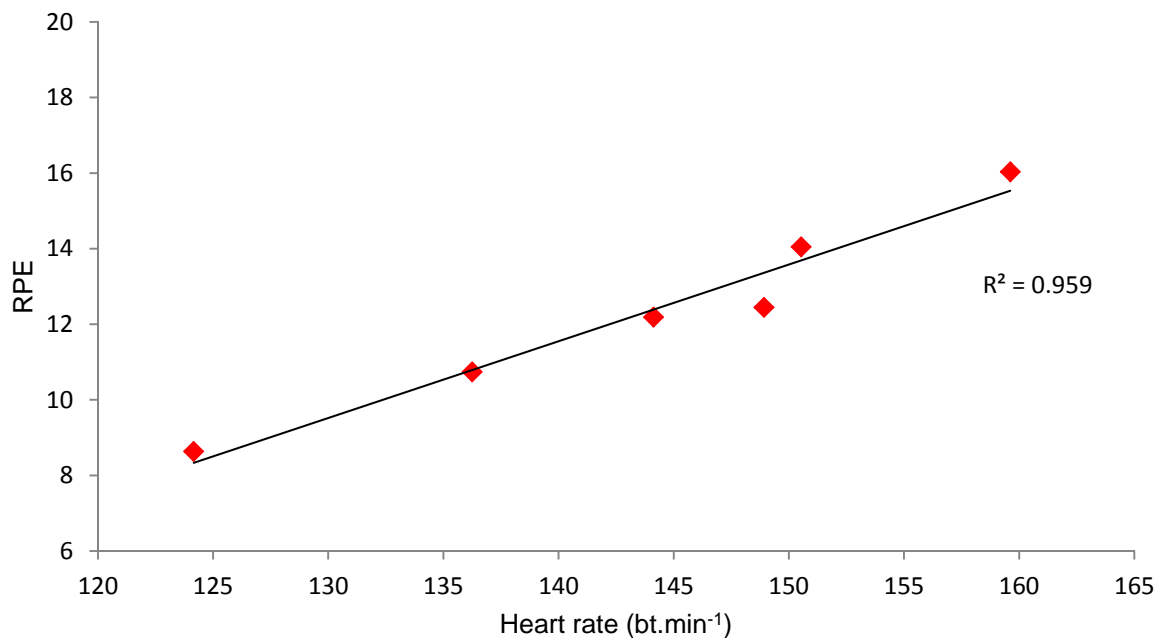


Figure 23: Correlation between heart rate and central ratings of perceived exertion.

There was a very strong, significant ($p < 0.05$) and positive correlation ($R^2 = 0.96$) between heart rate and central ratings of perceived exertion (Figure 23).

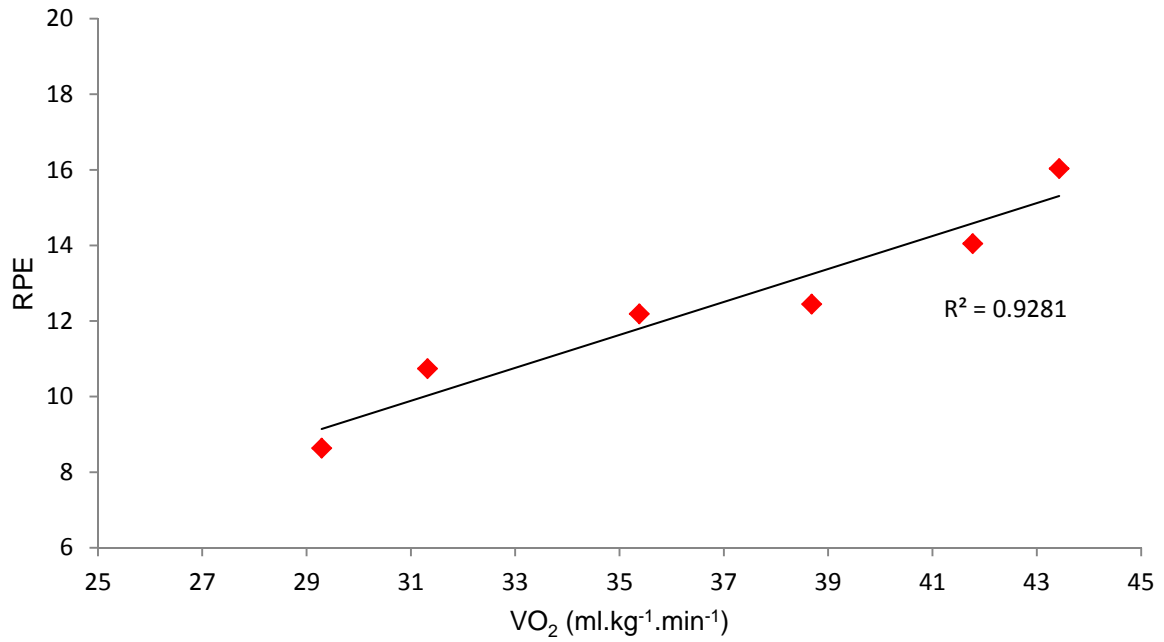


Figure 24: Correlation between VO₂ and central ratings of perceived exertion.

There was a strong, significant ($p < 0.05$) and positive correlation ($R^2 = 0.93$) between VO₂ and central ratings of perceived exertion (Figure 24).

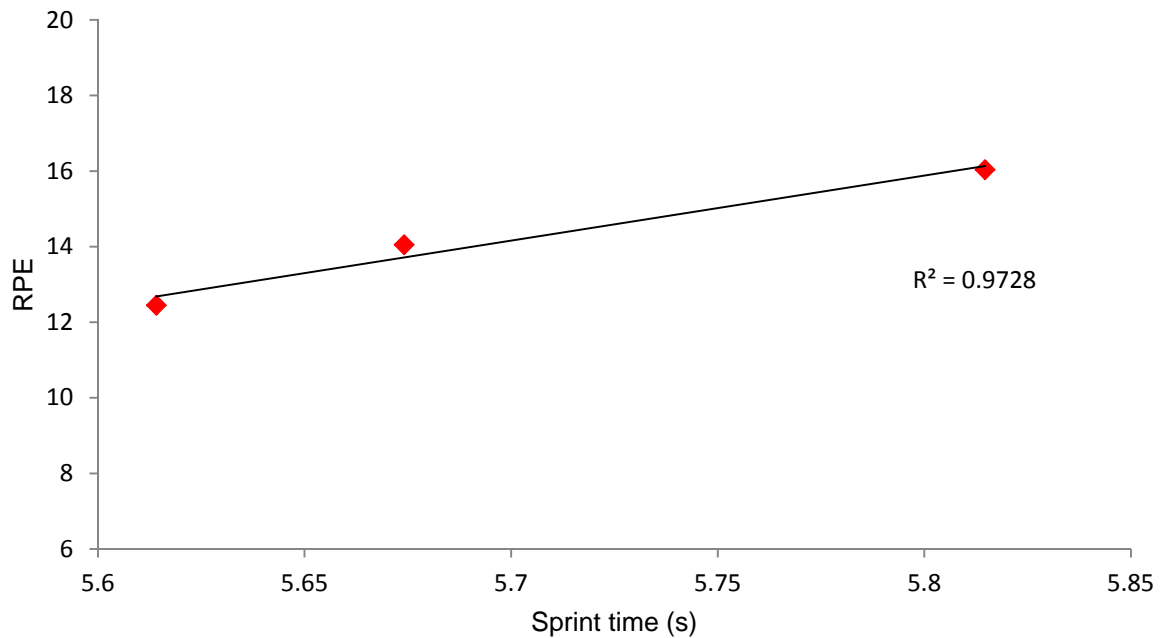


Figure 25: Correlation between sprint time and central ratings of perceived exertion.

There was a very strong, significant ($p < 0.05$) and positive correlation ($R^2 = 0.97$) between sprint time and central ratings of perceived exertion (Figure 25).

PERFORMANCE RESPONSES

SPRINT TIME BETWEEN WICKETS

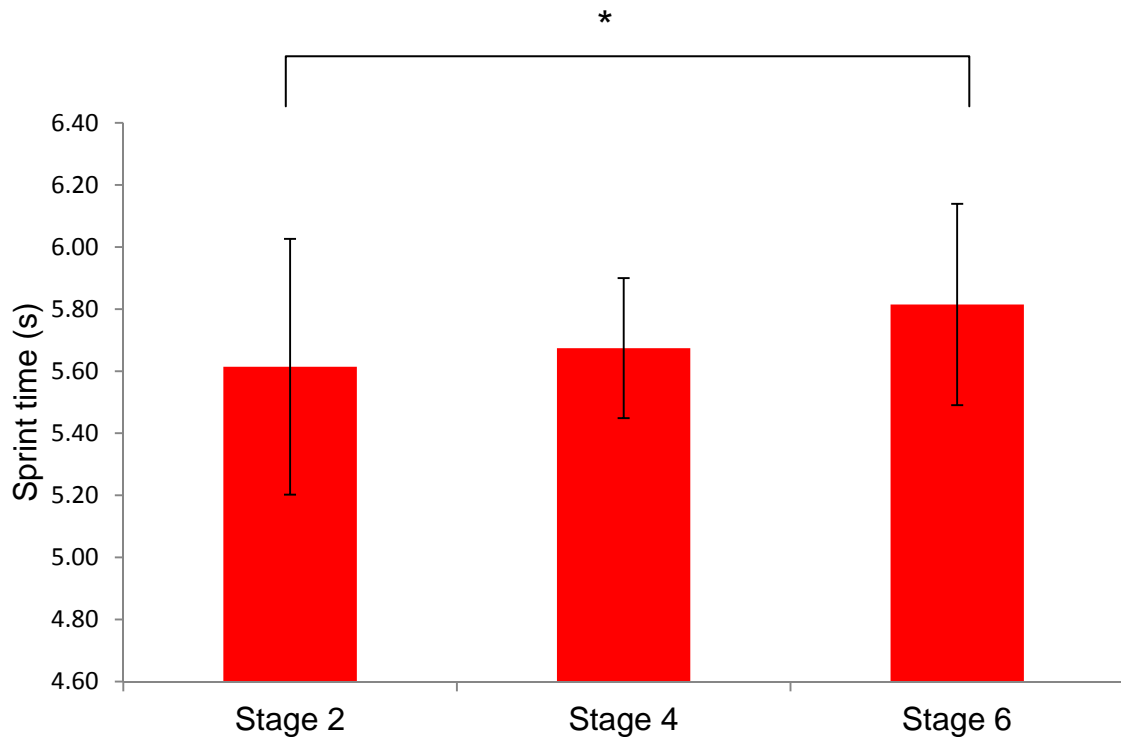


Figure 26: Mean (\pm SD) changes in sprint time between the high intensity stages of the protocol.

Where: * signifies a significant difference between stage two and six

The players' sprint times between the wickets were significantly lower ($p < 0.05$) during stage two (5.61 ± 0.41 s) than during stage six (5.81 ± 0.32 s), with no difference observed between stage four and the other high intensity stages (stages two and six) (Figure 26). Noteworthy was the high variance in stage two, and to a lesser extent in stage six, compared to stage four.

ACCURACY

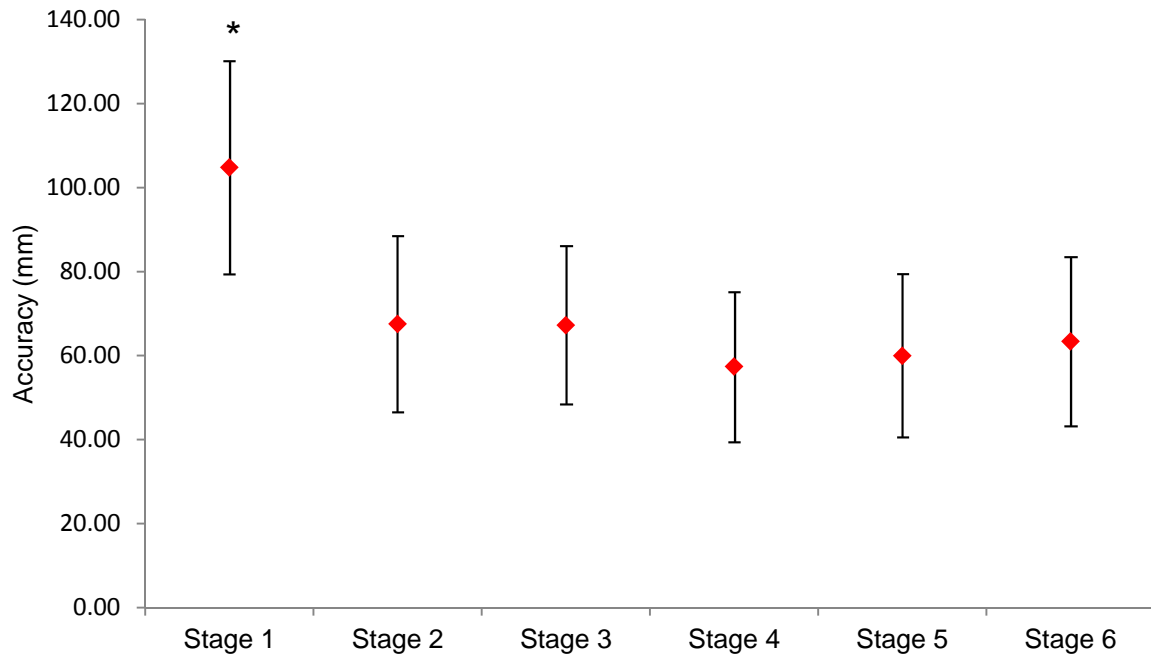


Figure 27: Mean (\pm SD) changes in the accuracy of the impact of the ball on the face of the bat.

Where: * denotes a significant difference between stage one and stage two-six

The displacement of the impact of the ball on the bat decreased significantly ($p < 0.05$) from stage one to two and then remained stable (Figure 27). The displacement of the ball from the sweet spot during stage one was 104.82 (± 25.34) mm and this decreased considerably (closer impact to the sweet spot i.e. accuracy improved) throughout the remainder of the protocol ranging between 57.40 (± 17.69) mm and 67.56 (± 20.84) mm. Noteworthy is the lower variation in accuracy scores compared to sprint times.

CHAPTER V

DISCUSSION

PHYSICAL CHARACTERISTICS

The physical characteristics of the batsmen that participated in the study are presented in Table VI (page 45). Although the participants represent a sub-elite group of batsmen, they displayed demographic, anthropometric and morphological characteristics similar to those of previous studies where national and international cricketers have been used as participants (Christie *et al.*, 2008; King, 2002; Noakes and Durandt, 2000).

A mean body mass index (BMI) of 24.85 (± 2.77) $\text{kg} \cdot (\text{m}^2)^{-1}$ indicates that the players fall into the 'normal' BMI category according to the World Health Organisation database on BMI. However, BMI is not the most accurate measure for describing a person's body proportions as it fails to take into account sex, age, body composition or activity levels. This can be seen when BMI is compared to the players' body fat percentage.

The mean body fat percentage, calculated from the sum of seven skinfolds, was 12.94 (± 2.40)%. This is similar to previous studies where body fat percentage was reported in batsmen: 12.4% (Christie *et al.*, 2008), 11.9% (King, 2002) and 12.47% (Noakes and Durandt, 2000). Furthermore, according to the American Council on Exercise guidelines, a body fat percentage of 12.94% indicates that players fall into the 'athlete' category (6-13% for men).

PHYSIOLOGICAL RESPONSES

HEART RATE (HR)

Heart rate increased from 124 (± 15.00) $\text{bt} \cdot \text{min}^{-1}$ during stage one to 159 (± 13.52) $\text{bt} \cdot \text{min}^{-1}$ during stage six (Figure 8; page 47). The largest change in heart rate occurred between the low intensity stage one and the high intensity stage two. This

increase in heart rate was an expected physiological response as oxygenated blood is supplied to the working muscles to ensure efficient removal of metabolic waste products (McArdle *et al.*, 2001).

The overall mean heart rate during the protocol was 144 (± 14.97) $\text{bt}\cdot\text{min}^{-1}$, which is similar to other sports such as soccer (Mohr *et al.*, 2012) and tennis (Fernandez *et al.*, 2006). With specific reference to batting, this was higher than heart rate responses reported by Gore *et al.* (1993), where players completed a simulated batting innings similar to a test match. These authors noted that heart rates of batsmen rarely rose above 128 $\text{bt}\cdot\text{min}^{-1}$. However, the heart rate data in the current study are similar to the findings of King (2002) and Christie *et al.* (2008), where heart rate reached a mean of 136 (± 13.00) $\text{bt}\cdot\text{min}^{-1}$ and 145 (± 11.00) $\text{bt}\cdot\text{min}^{-1}$ respectively. This is interesting as these latter two studies were high intensity work-bouts of short duration (approximately 20 minutes). However, the batsmen were only required to run a double shuttle every second ball, allowing for sufficient cardiovascular recovery between deliveries (King, 2002; Christie *et al.*, 2008). In contrast, heart rates were 15 $\text{bt}\cdot\text{min}^{-1}$ lower than that reported by Pote and Christie (in press). However, in the study by Pote and Christie (in press), the work-bout was also short (approximately 20 minutes) but more intense as a single run was sprinted every ball, not allowing for sufficient recovery periods. The only other study using a long duration protocol was that of Houghton *et al.* (2011a). Mean heart rates of their players was 130 $\text{bt}\cdot\text{min}^{-1}$; 14 $\text{bt}\cdot\text{min}^{-1}$ lower than in this study. This could be because the players in their study were of a higher calibre (club level players) than the players used in this investigation.

In contrast however, the heart rate responses in this study are comparable to data obtained during real match play. For example, Nicholson *et al.* (2009) measured heart rates between 139 and 154 $\text{bt}\cdot\text{min}^{-1}$ during 50 over games, and Petersen *et al.* (2010) reported a mean heart rate of 144 $\text{bt}\cdot\text{min}^{-1}$ during the same form of the game. In the current study, the work-bout was highly controlled in a laboratory setting, and thus heart rates would arguably be higher if players were exposed to actual game dynamics. So, while heart rates were similar to those recorded by Nicholson *et al.* (2009) and Petersen *et al.* (2010) the fact that game dynamics did not come into play gives further credence to the fact that the players in this study were not of the same level as previous investigations, which is a limitation of this study. It is well known

that several factors elevate a batsman's heart rate when batting in an actual match, including crowd dynamics, the pressure to perform, the type of bowler faced, the environmental conditions and the significance of the match (for example a world cup final compared to a normal ODI series against a lower ranked team).

Mean heart rate in this study was marginally lower than in Twenty/20 matches, where heart rates ranging between 149 and 167 $\text{bt}\cdot\text{min}^{-1}$ have been recorded (Nicholson *et al.*, 2009; Petersen *et al.*, 2010). Again, however, these were in actual game scenarios.

If the stages of the protocol are separated, the heart rate responses of the Christie *et al.* (2008) study and the current study are similar apart from stage one. This was to be expected as stage one was a low intensity stage whereas the protocol used by Christie *et al.* (2008) was high in intensity for all seven overs. This is further validated by the fact that a large effect size was observed between stages one and two in the current study. Heart rate measures were approximately 10 $\text{bt}\cdot\text{min}^{-1}$ -15 $\text{bt}\cdot\text{min}^{-1}$ lower in the Houghton *et al.* (2011a) study than in the current investigation when looking at the separate stages for high-grade batsmen; this excluded stage one. This is indicative once again of the training status of the players or it could be as a result of the 'touch and turn' that the players were required to perform. However, when the responses of the low-grade batsmen were compared between the two studies, responses were almost identical during each stage, showing a similar training status in the batsmen in this study and the low-grade batsmen in the Houghton *et al.* (2011a) investigation. Furthermore, if the real match data of Petersen *et al.* (2010), and Nicholson *et al.* (2009) is compared to the separate stages of the BATEX[®] work-bout, responses are very similar. This therefore suggests that the BATEX[®] protocol may be a valid training tool for ODIs and Twenty/20 matches, as heart rate responses recorded seem to replicate the demands of these formats of the game for each individual stage.

Another interesting finding is the effect of both intensity and duration on heart rate responses. Previous batting studies have indicated that the duration of the activity tends to have no impact on cardiovascular responses (Sheppard and Christie, in preparation). Sheppard and Christie (in preparation) however, only tested players for a seven over period, while in the current study the protocol was 30 overs. When

heart rate is examined over extended periods of time (like the BATEX[®] protocol) it seems as if this is not the case. In the current study it was shown that duration had a definitive effect on heart rate, as responses increased throughout the protocol for the different intensity stages (for example stage two: 148 ± 15.47 $\text{b.t.}\cdot\text{min}^{-1}$ compared to stage six: 159 ± 13.52 $\text{b.t.}\cdot\text{min}^{-1}$). Furthermore, it was also shown that intensity had an effect on heart rate, as responses expectedly decreased during low intensity stages and increased during high intensity stages. An interesting observation was that although the intensities stayed the same for stages one, three and five and stages two, four and six, heart rate still increased, which could indicate the occurrence of cardiovascular drift (Thompson, 2006). However, a more likely explanation is that the volume of runs completed in each of these different intensity stages increased as the protocol progressed, thus causing heart rate to rise. For example in stage two players were required to run 22 runs, in stage four 26 runs and in stage six 36 runs, all contributing to elevated heart rate responses over time.

BREATHING FREQUENCY (Rf), TIDAL VOLUME (VT) AND MINUTE VENTILATION (VE)

Breathing frequency (Rf), tidal volume (VT) and minute ventilation (VE) all followed the same trend, and responses decreased during the low intensity stages and increased during the high intensity stages. Peak Rf was $42.30 (\pm 3.96)$ $\text{br.}\cdot\text{min}^{-1}$ during stage six (resting= 12.00 $\text{br.}\cdot\text{min}^{-1}$), peak VT was $1.79 (\pm 0.23)$ L during stage four (resting= 0.5 L) and peak VE was $72.44 (\pm 10.08)$ $\text{l.}\cdot\text{min}^{-1}$ during stage six (resting= 6.00 $\text{l.}\cdot\text{min}^{-1}$), showing that the increased physical demands of the batting protocol caused ventilatory responses to rise (McArdle *et al.*, 2001). No significant differences were shown for Rf between stages two and three and stages four and five, indicating that players did not fully recover after the high intensity stages two and four. The fact that VE is dependent on Rf and VT means that when there is an increase in physical activity, such as during the high intensity stages of the batting protocol, players require more oxygen to be delivered to the working muscles and therefore there is an increase in both the frequency of breathing (Rf) and the volume of air that is breathed (VT). This, in turn, causes an increase in VE (McArdle *et al.*, 2001). Furthermore, increases in ventilatory responses may be due to the

enhancement of peripheral chemoreceptor activity or an increase in potassium, catecholamine concentrations and neural afferent signals in contracting muscle because of an increase in the frequency of limb movement (Drust *et al.*, 2000).

Responses were not in accordance with other intermittent sport profiles such as soccer, where mean VE responses have been shown to reach $81.30 \pm 10 \text{ L}\cdot\text{min}^{-1}$ (Drust *et al.*, 2000). To the author's knowledge, the only previous study done on ventilatory responses on batsmen found VE and VT responses which were approximately $7.00 \text{ L}\cdot\text{min}^{-1}$ and 0.55 L higher than in the current study (Christie *et al.*, 2008). This may be because this latter study employed a short duration, high intensity batting protocol (Christie *et al.*, 2008). The only ventilatory response that was higher in this study compared to Christie *et al.* (2008) was breathing frequency ($36.90 \pm 3.41 \text{ br}\cdot\text{min}^{-1}$ compared to $31.15 \pm 3.09 \text{ br}\cdot\text{min}^{-1}$). This could be due to two factors. Firstly it could be a result of the differences in the length of the work-bouts. The fact that the other physiological responses increased over the duration of the work-bout means that Rf would have to increase to ensure the supply of oxygen to the muscles. Secondly, studies have shown that breathing capacity does not reach maximum, even during strenuous exercise, and is not responsible for the limitations in oxygen delivery to the muscles (Burton *et al.*, 2004). It would therefore seem in this case that VT is the limiting factor as it has been shown that individuals increase their breathing frequency (it takes on a greater role) and not their VT, which leads to breathlessness (Baechle and Earle, 2008). This is clarified by the fact that there was no large effect size between stage one and two of the protocol for VT, compared to the large effect sizes observed for Rf and VE, but VT did peak after the drinks break. Furthermore, if the stages of the protocol are looked at separately and compared to the Christie *et al.* (2008) study, it can be seen that VE responses during the high intensity stages of two, four and six are very similar to those values recorded during the short-duration, high intensity protocol used by Christie *et al.* (2008), thus highlighting the increased demands of the high scoring stages of an ODI game. It was also noted that the training status of the players did not play a role in the difference in responses, as it has been shown that there are no differences in ventilatory responses between trained and untrained participants in response to brief intense intermittent exercise (Chamari *et al.*, 1995).

OXYGEN UPTAKE (VO_2) AND CARBON DIOXIDE PRODUCTION (VCO_2)

Oxygen uptake followed the same trend as heart rate responses, and increased from $29.92 (\pm 6.01) \text{ ml.kg}^{-1}.\text{min}^{-1}$ during stage one to $43.43 (\pm 6.30) \text{ ml.kg}^{-1}.\text{min}^{-1}$ during stage six (Figure 12; page 53). This is because there is a linear relationship between heart rate and oxygen uptake during most aerobic exercise intensities (McArdle *et al.*, 2001). The largest changes (large effect sizes) occurred between stages one and two, stages three and four and stages five and six. This was expected as these changes occurred during the transfer from low intensity to high intensity stages. When there was an increase in exercise intensity, there was an increase in heart rate and hence more oxygen was taken in so that the blood could supply the working muscles with oxygen.

Mean VO_2 during the simulated batting innings was $36.62 (\pm 6.30) \text{ ml.kg}^{-1}.\text{min}^{-1}$. This falls between 10.40 and $47.80 \text{ ml.kg}^{-1}.\text{min}^{-1}$, which is the range of VO_2 responses shown during tennis (Smekal *et al.*, 2001). Furthermore, this is considerably higher than shown in previous cricketing studies ($26.70 \pm 1.40 \text{ ml.kg}^{-1}.\text{min}^{-1}$ and $26.92 \pm 3.92 \text{ ml.kg}^{-1}.\text{min}^{-1}$) (Christie *et al.*, 2008; Pote and Christie, in press). This is interesting, as although the previous studies used short duration high intensity protocols, VO_2 responses were lower than in the current study. It may be because VO_2 rose dramatically during the high intensity stage two (stage one was similar to previous studies: $29.29 \pm 6.01 \text{ ml.kg}^{-1}.\text{min}^{-1}$), and then remained high throughout the rest of the protocol, indicating that the players may not have recovered sufficiently in the low intensity stages before performing the high intensity stages four and six.

Carbon dioxide production (VCO_2) followed a similar trend to VO_2 and increased and decreased with the low and high intensity stages respectively (Figure 13; page 54). The lowest VCO_2 was recorded during stage two ($26.07 \pm 5.43 \text{ ml.kg}^{-1}.\text{min}^{-1}$) and then increased until stage six, where it peaked at $26.07 (\pm 5.43) \text{ ml.kg}^{-1}.\text{min}^{-1}$. Although the lowest response was recorded during stage two, this value was very similar to that of stage one ($26.46 \pm 6.06 \text{ ml.kg}^{-1}.\text{min}^{-1}$). The increases in VCO_2 responses when the players started to sprint may be a reflection of the amount of CO_2 eliminated to compensate for changes in the acid-base balance (Chamari *et al.*, 1995). Large effect sizes were also observed for VCO_2 responses. This can be explained by looking at the oxyhemoglobin dissociation curve. As partial pressure

increases, carbon dioxide content rises and the curve shifts to the right (Arthurs and Sudhakar, 2005). Furthermore, the rise in VCO_2 with exercise is associated with the onset of metabolic acidosis, and to compensate for this alveolar ventilation must increase to eliminate the excess CO_2 being produced. This in turn results in a decrease in bicarbonate concentration (Wasserman, 1966). The respiratory system also compensates acidosis during exercise by causing an increase in VE (Figure 11, page 51), so that pH levels in the body remain normal (Wasserman, 1966). If the low and high intensity stages are separated it can be seen that VCO_2 responses remained fairly similar throughout the protocol. This may be due to an increased aerobic contribution to energy metabolism (Chamari *et al.*, 1995).

RESPIRATORY EXCHANGE RATIO (RER)

Mean respiratory exchange ratio (RER) during the full protocol was 0.90 (± 0.18), which is lower than in the only other cricket study which has reported on this response (Christie *et al.*, 2008: 1.05 ± 0.05). However, this study used a short duration, high-intensity protocol and it is well known that more carbon dioxide is produced with high intensity efforts, which results in an increase in RER (McArdle *et al.*, 2001). This also explains why only stage one of the current study elicited a similar response to the Christie *et al.* (2008) investigation.

The highest RER was recorded during stage one (0.95 ± 0.19) and stage two (0.95 ± 0.18) (Figure 14; page 55). Thus players were utilising mainly carbohydrates as an energy source (Brooks and Mercier, 1994). Responses then decreased during stage three (0.86 ± 0.16), indicating a shift in substrate utilisation to a lesser reliance on carbohydrates (Brooks and Mercier, 1994). After the drinks break a slight rise in RER was observed during stage four (0.92 ± 0.19). This can be attributed to the ingestion of an Energade (645 kJ; 39 g CHO) during the break, which resulted in a higher carbohydrate utilisation from the ingested glucose. RER then decreased again during stage five (0.84 ± 0.17) and stage six (0.89 ± 0.18), indicating a reduced reliance on carbohydrate stores and a greater reliance on fats as an energy source. This is because it is well known that as exercise duration increases, so too does an individual's reliance on fats (Dunford and Doyle, 2012).

Like heart rate, RER responses were also affected by both the duration and the intensity of the protocol. If the high and low intensity stages are separated it can be seen that RER decreases from stage one, to stage three and stage five for the low intensity stages, and from stage two, to stage four and stage six for the high intensity stages. This shows the effect of exercise duration on RER. However, if all the stages are looked at together, we can see that the low intensity stages exhibit much lower RER responses than the high intensity stages, therefore indicating the effect of exercise intensity. The only exception is between stage one and two, where responses are the same, but this can be explained by the fact that it was the beginning of the protocol and players had not yet used up muscle glycogen stores. These shifts in substrate utilisation may be an indication that the players were becoming fatigued towards the end of the work-bout (Brooks and Mercier, 1994).

ENERGY EXPENDITURE (EE)

There are very few comparisons of energy expenditure responses in intermittent sports. Most studies that have looked at energy cost have used prediction equations, which are not as accurate as the methods used in the current study. Energy expenditure followed the same trend as the ventilatory responses, increasing and decreasing with the low and high intensity stages respectively (Figure 15; page 57). This is because with an increase in exercise intensity there is an increase in heart rate and hence the total amount of energy expended also increases (Dunford and Doyle, 2012). The lowest energy expenditure was recorded during stage one ($11.49 \pm 2.04 \text{ kcal.min}^{-1}$), and responses peaked during stage six ($16.90 \pm 2.53 \text{ kcal.min}^{-1}$). We know that at the onset of exercise there is an increase in heart rate in order to provide oxygenated blood to the working muscles (McArdle *et al.*, 2001). At the same time there is also an increase in energy expenditure, which causes adjustments in blood flow, and this in turn affects the cardiovascular system (McArdle *et al.*, 2001).

To compare energy expenditure responses in this study to previous investigations, responses were converted from kcal.min^{-1} to kJ.h^{-1} . The mean energy expenditure of this investigation was therefore $3581.54 (\pm 2.01) \text{ kJ.h}^{-1}$. This falls between $1630.34 \text{ kJ.h}^{-1}$ and $4237.88 \text{ kJ.h}^{-1}$, which has been displayed in studies conducted on tennis

players (Coelho *et al.*, 2010), meaning that the energy cost of batting is similar to other intermittent sports. Furthermore, according to McArdle *et al.* (2001), this shows that the exercise intensity of the protocol was 'unduly heavy' indicating that batting, and in particular, scoring a century, is highly physiologically taxing. Factors influencing this include the different periods of low and high intensity running, the acceleration and deceleration while initiating and ending a run, and the turning between wickets when running more than a single run.

The energy cost of this study is also substantially higher than the 650 kJ.h⁻¹ proposed by Fletcher in 1955. However, the game has changed greatly since then. According to Woolmer *et al.* (2008) the physical cost of batting can be compared to 21 km and 42 km running races, which is substantially higher than originally thought. Other studies performed on batsmen in particular have shown responses of 2536 kJ.h⁻¹ (Christie *et al.*, 2008) and 2777.83 kJ.h⁻¹ (Pote and Christie, in press). Although these responses are lower than the 3581.54 (±2.01) kJ.h⁻¹ recorded during the current investigation, this was to be expected as batsmen batted for a much longer time in this study, and they ran a higher number of runs and performed the protocol at low and high intensities. In the previous studies players were required only to bat for a short time (seven overs) and run at an all-out intensity.

Another factor that may have affected energy expenditure in the current study was the fact that batsmen were instructed to 'touch and turn' at the non-striker's end when running a single as if looking for another run (the same as batsmen execute in a match situation). Other studies required their batsmen to 'run through' only when completing a single, and no turning was required (Houghton *et al.*, 2011a; Pote and Christie, in press). This 'touch and turn' was required as previous research has shown that the deceleration, turning at the crease and then re-acceleration has an impact on energy cost (Pote and Christie, in press). Furthermore, the fact that other physiological responses such as heart rate are not affected by this occurrence means that this extra energy cost may be a result of changes in the players' muscle and force-producing capabilities required when turning for another run (Pote and Christie, in press). Therefore, the acceleration which is essential to complete a second run, results in increased forces in the hip, knee and ankle muscles, and this in turn is likely to increase the energy cost when running a 'two' (Pote and Christie, in press).

CORE TEMPERATURE (T_c)

Core temperature increased from stage one (37.65 ± 0.27 °C) until the end of stage three (38.39 ± 0.30 °C) (Figure 16; page 59). Responses then decreased during stage four (38.17 ± 0.80 °C) and once again increased during stage five until peaking at $38.70 (\pm 0.37)$ °C during stage six, which is well above resting T_c of 37.00 °C. A large effect size was observed between stages one and two, which was due to the body adapting at the onset of exercise.

Mean T_c for the current study was $38.26 (\pm 0.40)$ °C, which compares to other intermittent sports such as rugby and soccer, where core temperatures have been shown to range between 38.50 °C and 39.38 °C (Duffield *et al.*, 2009). Other studies on rugby union players in our department also showed core temperatures ranging between 37.29 °C and 38.95 °C (Cannon, 2010). Studies on cricketers in particular have shown much lower temperatures than the current study (33.69 °C to 35.90 °C), but these experiments measured tympanic, skin and forehead temperatures (King, 2002; Houghton *et al.*, 2011a). Other literature suggests that the ingestible pill is a more widely acceptable measurement of T_c in an exercise and sport setting (Leong Lim *et al.*, 2008). Similar temperatures (38.30 ± 0.02 °C) have been recorded by Gore *et al.* (1993), but rectal temperature was used, which is not affected by ambient conditions and is therefore more accurate than the previously mentioned measuring techniques (Leong Lim *et al.*, 2008). The only other study to observe temperatures over extended periods of time (using the BATEX[®] protocol), showed a mean temperature of $35.90 (\pm 0.90)$ °C, but tympanic temperature was used for the temperature measurement, therefore explaining the large deviation between the two studies (Houghton *et al.*, 2011a). The temperatures recorded during the Houghton *et al.* (2011a) investigation showed a 0.30 °C rise in temperature over the 30 over protocol, whereas the current study showed a 1.05 °C increase. This could be ascribed to the fact that testing during the Houghton *et al.* (2011a) study took place outdoors, while the current study was performed in a laboratory setting. Furthermore, although in the current study core temperature dropped after the drinks break, there was still a 1.36% increase in core temperature between stage one and stage five, indicating that although T_c dropped after the drinks break, players did not fully recover. The same trend was seen in the rugby study performed by Cannon (2010), where the ingestible pill was used to measure T_c . This trend was not

observed during the Houghton *et al.* (2011a) study though, once again indicating the limitations of using tympanic temperature measurements. Other factors that may have affected T_c during these investigations include glycogen depletion, hypohydration, and accumulation of potassium in the muscle interstitium and the players' increased perception of effort towards the end of the protocol (Duffield *et al.*, 2009).

The increases in T_c can be attributed to the running requirements of the protocol. During exercise energy metabolism needs to be maintained by the delivery of arterial blood to the muscles (Charkoudian, 2003). Furthermore, arterial blood flow needs to be diverted to the periphery to promote cooling at the surface of the skin, but because of this oxygen cannot be delivered to the active muscles (McArdle *et al.*, 2001). Although the body tries to cope with this through vasodilation and sweating, blood pressure still needs to be maintained and therefore there is a rise in the players' T_c (Charkoudian, 2003; McArdle *et al.*, 2001). In other words, the active muscles required additional blood flow, therefore compromising blood flow to the skin and thus limiting heat transfer to the environment. The drop in T_c at the beginning of stage four can be ascribed to the drinks break. During the drinks break players were required to consume an Energade (645 kJ; 39 g CHO's), and no running between the wickets was completed, therefore causing a decrease in the players' T_c . This highlights the importance of proper hydration and rest breaks in decreasing players' T_c responses and thereby probably improving performance.

Core temperature was, however, well below the 40.00 °C mark where it has been suggested that there is a risk of developing a heat-related illness (Duffield *et al.*, 2009). Traditionally, it was thought that at critical temperatures the cardiovascular and metabolic systems become overloaded, therefore reducing exercise performance (Duffield *et al.*, 2009). Recently it has been suggested that reductions in the central nervous system drive and the down regulation of neural recruitment and muscle activation help to regulate T_c so as not to reach a 'critical' threshold (Duffield *et al.*, 2009). This lends support to the central governor hypothesis proposed by Noakes (2000), where individuals appear to self-regulate themselves to prevent extreme rises in T_c .

SWEAT LOSS AND SWEAT RATE

Mean absolute sweat loss was 1.48 L while relative sweat loss was 1.83% (Figure 18; page 61). This was expected as the main method of heat loss during exercise is through sweating (McArdle *et al.*, 2001). When the body is subjected to any type of heat stress, such as performing the batting work-bout, sweat glands, which are controlled by cholinergic sympathetic nerve fibres, secrete large quantities of hypotonic saline solution (McArdle *et al.*, 2001). Research has shown that exercise at high intensities can produce sweat rates of between 1.00 and 2.50 L.h⁻¹. Other studies have shown sweat rates of 1.5 L.h⁻¹ for rugby players (Gore *et al.*, 1993) and 2.00 L.h⁻¹ for tennis players (Tippet *et al.*, 2011). In the studies that have been performed on cricketers, sweat rates have ranged between 0.47 L.h⁻¹ and 0.93 L.h⁻¹ (Gore *et al.*, 1993; King, 2002; Houghton *et al.*, 2011a). Furthermore, sweat rates for ODI games have been shown to range between 0.30 (± 0.31) L.h⁻¹ and 1.44 (± 0.125) L.h⁻¹ (Brearly and Montgomery, 2002; Soo and Naughton, 2007). The differences in the sweat rates can be attributed to the different lengths and intensities of the work-bout. Mean sweat rate for the current study was 0.64 L.h⁻¹, which falls within the range for ODI matches, therefore showing that the study is an accurate representation of the batting demands in an ODI game. The long duration study performed by Houghton *et al.* (2011a), showed a mean sweat rate of 0.90 (± 0.13) L.h⁻¹. This is higher than in the current study, which may be explained by the studies using different calibre players, as it is well known that sweat rate is greater in players who are better trained (Buono and Sjöholm, 1988). It may also be due to the different testing environments used (outdoors compared to laboratory setting).

An increased sweat response also indicates that there is an increase in the physiological strain experienced by the players (King, 2002), which is evident when the physiological variables of this study are examined. Sweating can also be affected by the protective gear worn by batsmen. Protective gear (in this study: pads, gloves, thigh guard and box) impede the evaporation of sweat, therefore reducing the amount of heat lost through sweating (King *et al.*, 2002). This in turn causes a rise in core temperature, which has been shown to cause a reduction in exercise performance (Duffield *et al.*, 2009).

PERCEPTUAL RESPONSES

CENTRAL RATINGS OF PERCEIVED EXERTION (RPE)

As with most of the other responses, the players' central ratings of perceived exertion increased and decreased according to the low and high intensity stages (Figure 20; page 62). This indicates that the players acknowledged the increase and decrease in work being performed. The lowest rating was recorded during the first stage (8.63 ± 1.54), while the highest rating was recorded during the last stage (16.04 ± 0.86).

Although traditionally Borg's RPE rating scale has been used as a subjective rating of exercise intensity, more recently it has been suggested that RPE also increases as a function of exercise duration (Noakes, 2011). Figure 21 (page 63) and Figure 22 (page 63) however, shows the low and high intensity stages separately for the duration of the protocol. The fact that the intensity stayed the same, but players' RPE still increased, shows that RPE increased as a function of exercise duration and not intensity. However, as with heart rate, this could also be due to the volume of runs increasing for each different intensity stage throughout the protocol (for example 22 runs in stage two compared to 36 runs in stage six). Furthermore, it has also been suggested that the rise of RPE responses may also be affected when a player knows the end-point of the work-bout, as the brain uses this knowledge to regulate exercise and to prevent failure of the organs of the body (Noakes, 2011; Pote and Christie, in press). This may also be linked to pacing strategies, and further research may be required to determine how knowledge of the end-point of exercise affects players' perceived effort.

A strong, significant ($p < 0.05$) and positive correlation ($R^2 = 0.96$) was observed between the players' central RPE and heart rate (Figure 23; page 64). This shows that players were well habituated to the RPE scale (the concept of a subjective rating tool was well understood) and that their perceived effort was an accurate reflection of the work-bout. Furthermore, RPE can be used as an accurate predictor of heart rate responses to indicate physiological strain. This has also been shown in other cricketing studies (King, 2002: $R^2 = 0.94-0.99$; Pote and Christie, in press: $R^2 = 0.94$). When RPE responses are compared between the current study and the Houghton *et al.* (2011a) study it can be seen that the mean responses are very similar (12

compared to 13). During the separate stages, responses are also very similar between the investigations, thus further showing the reliability of using RPE as a predictor of physical activity. Although this has been shown in cricketing studies previously, it has not been revealed over extended periods of batting activity. A strong and significant ($p < 0.05$) correlation ($R^2 = 0.93$) was also observed between VO_2 and RPE (Figure 24; page 65). This shows that VO_2 is an accurate measure of physiological load. Therefore we can convincingly say that RPE can be used to predict VO_2 and hence energy expenditure. Furthermore, a very strong and significant ($p < 0.05$) correlation ($R^2 = 0.97$) was observed between sprint times and RPE (Figure 25; page 65). This confirms that sprint time is a reliable performance indicator as players perceived more difficulty over time which was demonstrated by an increase in their sprint times.

PERFORMANCE REPONSES

SPRINT TIME AND ACCURACY

Figure 26 (page; 66) shows the players' sprint time between the wickets. The fact that only three of the six stages of the BATEX[®] were all-out, high-intensity stages meant that sprint times were measured only during stages two, four and six.

We know from the study performed by Houghton *et al.* (2011b) that sprint time between the wickets is a reliable performance indicator during a prolonged, simulated batting protocol. The sprint time findings in the current study are similar to the only other study which has measured responses during the BATEX[®] protocol (Houghton *et al.*, 2011b). Participants in the Houghton *et al.* (2011b) study performed two trials. During the first trial participants performed the full BATEX[®] protocol after a two hour pre-test fast, and one-two weeks later performed the second trial after a 24 hour diet replication. Mean 5-0-5 m turn time (time from the five meter sensor to the bowling crease and back again) increased (stage two-stage six) during trial one but not during trial two. This was explained by the fact that players were more resistant to fatigue in stage two as a result of more practice in running between the wickets (Houghton *et al.*, 2011b). The same findings were observed in the current study, and the increase in sprint times could also be

explained by the fact that players were not experienced in running between the wickets, as is the case with international batsmen. If another trial was performed in this study, perhaps players' sprint times would have remained similar due to familiarity with the protocol or due to players implementing pacing strategies. Houghton *et al.* (2011b) also noted that when high and low-grade batsmen were compared there was a small trend for better running between the wickets performance, which can also be explained by experience. Sheppard and Christie (in preparation) also looked at sprint times in a study conducted in our laboratory, and although a short-duration, high-intensity work-bout was used, where players ran two runs every ball for seven overs, sprint times also increased over time. This increase in sprint time may be an indicator that players are becoming fatigued towards the back end of an innings. This is further validated by other studies that have looked at fatigue as a result of an increase in sprint times (Glaister *et al.*, 2008; Small *et al.*, 2009; Buchheit *et al.*, 2010).

If the players are becoming fatigued, this is probably due to two main factors: either the rest periods are not sufficient and therefore there is an increase in sprint time (players get slower) due to the lack of recovery, or the increased eccentric load placed on the muscles due to the constant acceleration, deceleration and turning during running between the wickets causes a decrease in performance due to decrements in muscle force-producing capabilities (Sheppard and Christie, in preparation). Although it has been shown in previous studies that the stop start nature of a cricket game allows for sufficient recovery time of the cardiovascular system (Christie *et al.*, 2008), this information is based on short-duration protocols. No studies have examined this effect over extended periods of play. Therefore, it seems in this case that if players are becoming fatigued, it is likely to be linked to the fact that there was not sufficient recovery time of the musculoskeletal system throughout the protocol. Furthermore, the fact that players got slower towards the end of the protocol, indicates that there was a decrease in the force-generating capacity of the muscle. It would therefore be expected that heart rate responses would decrease over time, but we have already seen that heart rate increased as a function of duration and intensity. Therefore, the fact that heart rate increased, but there was a decrease in the force generating capacity of the muscle shows that down-regulation was taking place (Noakes, 2011).

Another factor that has been known to affect sprint times is knowledge of the end-point of the work-bout. Studies in our department have shown that when batsmen know the end-point of exercise or the protocol, they subconsciously pace themselves (Christie and Armstrong, 2012; Sheppard and Christie, in preparation). This strategy of pacing links to what is known as the central governor hypothesis, where the brain paces the body while performing an exercise in order to ensure that the activity is completed without any large homeostatic imbalances in the body (Noakes *et al.*, 2005). This is controlled by changes in the recruitment of skeletal muscle and by the inhibitory effects of the brain telling the body that it is fatigued, when in actual fact it can continue to operate at an optimal level (Noakes *et al.*, 2005). However, while this effect has been noted in previous studies, in this investigation there was no evidence of pacing, even though the end-point of the work-bout was known by the participants.

In terms of accuracy, during stage one of the protocol, the displacement of the ball from the sweet spot of the bat was 104.82 ± 25.34 mm (Figure 27, page 67). This decreased significantly (accuracy increased) after stage one and averaged $63.11 (\pm 4.46)$ mm between stages two and six. This would suggest that it takes a certain amount of time for batsmen to analyse the bowler's run-up, watch the ball through the air, assess its line and length, determine the lateral deviation off the pitch and determine its speed before executing a shot based on this information (Stretch *et al.*, 2002). In this study this assessment seems to have taken place in the first stage of the protocol, which would be the beginning of a batsman's innings in a match situation. After this the batsman is aware of these factors and is therefore able to execute a more precise shot due to the knowledge gained at the beginning of their innings. In cricket this is more commonly referred to as batsmen 'getting their eye in'. However, in this study the batsman did not have to analyse the bowler's run-up as the ball was delivered from a bowling machine, and each was delivered at the same speed and on the same line and length. This being said, in a real match situation, this is not the case and every ball is different, so in terms of accuracy, the analysing process may take longer than shown in this investigation.

If we look at sprint time and accuracy together, it would seem as if sprint time is affected by the century work-bout, but accuracy is not. However, the fact that accuracy is also dependent on cognitive factors may indicate that although players

may have been physically fatigued, which impacted sprint time responses, this physical fatigue did not impact the batsmen cognitively. The cognitive aspect (accuracy) was also less varied, showing that the batsmen were skilled and the sample was similar, whereas the variation in sprint times was probably due to differences in physical fitness. Furthermore, the fact that this study was not an actual match situation could have caused the batsmen to focus more on accuracy than on sprint time, as they knew that there was no chance of being run out. So, the pressures associated with playing an actual match may have affected these responses differently.

CONCLUSION

Batting for extended periods of time, such as during the BATEX[®] protocol, significantly influenced the physiological, perceptual and some performance responses of the players. Increases in the physiological and perceptual responses over time, as well as an increase in the players' sprint times, may be an indicator of physical fatigue as a consequence of extended batting. Furthermore, the fact that accuracy improved significantly after the first stage indicates that although players may have been physically fatigued, this had no impact on the batsmen's concentration or cognitive processes. Although other studies have shown participants implementing pacing strategies while exercising for long periods where the end-point is known, the current study displayed no evidence to suggest that any pacing was taking place. The results therefore suggest that the constant running between the wickets, while batting for extended periods of time, affects the physical load placed on players, influencing sprint times but not accuracy.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY OF PROCEDURES

Seventeen male, university and country districts cricketers ranging between the ages of 18 and 27 years, performed the BATEX[®] protocol in a laboratory setting. Participants were required to attend two testing sessions, one at the Human Kinetics and Ergonomics Department in Grahamstown, South Africa, and the other at the Kingswood College High Performance Centre in Grahamstown, South Africa.

During the first testing session the BATEX[®] protocol was explained to the players both verbally and in writing. Players were then asked to sign an informed consent form and fill out a physical activity screening questionnaire to determine whether there were any serious injuries or medical conditions. The participants were also habituated to the protocol and the equipment to be used and the rating of perceived exertion (RPE) scale was explained in detail. Basic anthropometric, demographic and morphological data were collected and players were given the ingestible CoreTemp[®] pill to swallow two hours before performing the work-bout as well as a set of pre-test instructions that they were asked to follow strictly. Once completed, participants were given the opportunity to ask questions.

During the second testing session, players were required to complete the BATEX[®] protocol. On arrival at the High Performance Centre players performed a warm-up to avoid injury and then padded up in full cricket kit. Participants were then fitted with the k4b² (Cosmed[®], Rome), and the CoreTemp[®] monitoring system was used to check if a signal was being sent from the ingestible pill. Once this was completed, the players performed the batting work-bout which consisted of batting for thirty overs and running at different intensities, typical of scoring a One Day International century. Balls were delivered at 105 km.h⁻¹ by a research assistant from a bowling machine. Players were given a 35 s break between deliveries and an 80 s break between overs. There was also a 2 minute 30 second break at the end of each stage and a 4 minute break at the halfway point of the protocol. Throughout the

work-bout physiological, perceptual and performance responses were recorded. After completion of the protocol players participated in a cool-down session involving cricket-specific stretches.

Dependant variables of interest for the study were:

Physiological variables: heart rate, oxygen uptake, energy expenditure, breathing frequency, tidal volume, minute ventilation, respiratory exchange ratio, core temperature and sweat loss.

Perceptual variables: Central ratings of perceived exertion

Performance variables: Sprint time between the wickets and accuracy of the impact of the ball on the bat.

SUMMARY OF RESULTS

PHYSIOLOGICAL RESPONSES

Heart rate responses showed significant differences ($p < 0.05$) between all stages except between stages two and four, two and five and stages four and five. Responses increased and decreased accordingly with the high and low intensity stages. In terms of effect size, the only large change was between stages one and two.

Significant changes ($p < 0.05$) were shown between all stages except between stages two and three and stages four and five for breathing frequency responses. Responses followed the same trend as heart rate, increasing during the high intensity stages and decreasing during the low intensity stages. Large effect sizes were observed between stages one and two and stages three and four.

Tidal volume responses showed significant differences ($p < 0.05$) between the high and low intensity stages. Large effect sizes were observed between all the stages except between stages one and two.

Minute ventilation responses showed significant differences ($p < 0.05$) between all the stages except between the low intensity stages one and three and the high intensity

stages four and six. A very large effect size was observed between stages five and six, while the other stages presented large effect sizes, except between stages three and four.

Significant differences ($p < 0.05$) were seen for oxygen uptake responses between all stages except between stages one and three and stages four and six. Large effect sizes were observed between stages one and two, stages three and four and stages five and six.

Carbon dioxide production followed the same trend as tidal volume, and significant differences ($p < 0.05$) were shown between the low and high intensity stages. However, large effect sizes were seen between all the stages.

The respiratory exchange ratio (RER) showed significant differences ($p < 0.05$) for all the stages except between stages one and two, stages two and four and stages three, five and six. Unlike other responses, the highest RER was recorded during stage one and two. Only trivial and small effect sizes were observed between stages.

Energy expenditure responses showed significant changes ($p < 0.05$) between all the stages except between stages one and three, stages two and four and stages four and six. Large effect sizes were seen between all the stages except between stages four and five, where a moderate effect size was observed.

Significant differences ($p < 0.05$) were observed for core temperature responses between stage one and stages two-six and between stages two and six and stages four and six. The only large effect size was seen between stages one and two.

A significant drop ($P < 0.05$) in body mass was observed post the simulated batting protocol.

PERCEPTUAL RESPONSES

Central ratings of perceived exertion (RPE) increased significantly ($p < 0.05$) over time except between stages two and five. A strong, positive and significant ($p < 0.05$) correlation ($R^2 = 0.96$) was also observed between heart rate and central RPE.

PERFORMANCE RESPONSES

Sprint times between the wickets were significantly lower ($p < 0.05$) during stage two than during stage six. High variance was also observed during stage two compared to stage four and stage six.

Accuracy of the impact of the ball on the bat increased significantly ($p < 0.05$) from stage one to stage two and then stabilised for the remainder of the protocol, showing the ball was impacting closer to the sweet spot of the bat after stage one.

STATISTICAL HYPOTHESES

PHYSIOLOGICAL HYPOTHESES

With respect to hypothesis 1a:

- (i) The results force the rejection of the null hypothesis as significant changes ($p < 0.05$) for heart rate responses were observed between the majority of the overs.
- (ii) The results force the rejection of the null hypothesis as significant differences ($p < 0.05$) for oxygen uptake and energy expenditure responses were observed between the majority of the overs..

With respect to hypothesis 1b:

- (i) The results force the rejection of the null hypothesis as breathing frequency responses exhibited significant changes ($p < 0.05$) between the majority of the overs.
- (ii) The results force the rejection of the null hypothesis as significant changes ($p < 0.05$) were observed for tidal volume responses between the majority of the overs..

- (iii) The results force the rejection of the null hypothesis with regards to minute ventilation, as significant differences ($p < 0.05$) were observed between the majority of the overs.
- (iv) With regards to the respiratory exchange ratio, the results reject the null hypothesis as significant changes ($p < 0.05$) were observed between the majority of the overs.

With respect to hypothesis 1c:

- (i) The results force the rejection of the null hypothesis as significant differences ($p < 0.05$) were observed in core temperature responses between the majority of the overs.
- (ii) In terms of body mass pre and post protocol (sweat loss), the results force the rejection of the null hypothesis as significant changes ($p < 0.05$) were observed.

PERCEPTUAL HYPOTHESIS

With respect to hypothesis 2, the significant changes ($p < 0.05$) over time force the rejection of the null hypothesis for the majority of the perceived ratings. This excludes between stages two and five where the null hypothesis is tentatively retained.

PERFORMANCE HYPOTHESES

With respect to hypothesis 3a, the null hypothesis is tentatively retained as no significant differences were observed over time with regards to the accuracy of the impact of the ball on the bat. This excludes between stage one and two where significant ($p < 0.05$) differences were observed and in which case, the null hypothesis is rejected.

With regards to hypothesis 3b, significant changes ($p < 0.05$) were observed over time in sprint times between the wickets, therefore forcing the rejection of the null hypothesis, except between stages two and four and stages four and six. In these instances, the null hypotheses are tentatively retained.

CONCLUSION

The aim of the study was to determine the physiological and perceptual responses of batting during a simulated One Day International (ODI) century, and to determine how these responses affected batting performance. The results showed that the physiological and perceptual responses were significantly affected while performing the simulated BATEX[®] protocol. This was a result of both the intensity and duration of the work-bout, thus showing that the physical demands of batting in an ODI are a lot more substantial than originally thought. This is especially important since the current study is one of the only investigations to observe a multitude of responses during extended periods of play. The increase and decrease in perceptual responses, and the correlation between heart rate and central ratings of perceived exertion, showed that the players accurately perceived the demands of the work-bout.

The increases observed in the physiological and perceptual responses also significantly impacted the performance measures. It would seem as if sprint time is affected by an increase in physiological responses, as times were significantly slower towards the end of the protocol, indicating that players may have been physically fatigued. However, accuracy responses improved after the first stage of the protocol, indicating that the players' cognitive processes and concentration were not affected by an increase in physiological responses. Furthermore, while previous studies have indicated that players self-regulate themselves when the end-point of exercise is known, there was no evidence in this investigation of any pacing strategies being implemented.

Overall, it can be concluded that the physical nature of scoring an ODI century significantly affects perceptual and performance measures, indicating that cricket,

and more specifically batting in cricket, is more physically demanding than previously thought.

RECOMMENDATIONS

With regard to future studies seeking to examine the impact of physiological and perceptual responses over time on batting performance, the following recommendations need to be taken into account:

1. The current study was conducted in a laboratory setting. Future studies should record responses during actual match-play situations, so that variables such as crowd dynamics, match pressure, different types of bowlers and different environmental conditions can also be taken into consideration. These variables will have an impact on the responses recorded during an actual One Day International match.
2. Due to the equipment utilised in the study, it was not possible to fit the players with all batting protective gear such as helmets and chest guards. Studies should consider the use of full protective equipment in the future as this may affect mechanisms of heat loss, therefore influencing core temperature measurements.
3. Studies have indicated that the constant acceleration, deceleration and turning between wickets during batting affects the lower limb musculature (more specifically the hamstrings and quadriceps), which may lead to fatigue. Future investigations should consider the demands placed on the lower limb musculature, especially over extended periods of batting.

4. The addition of a control and an intervention group should be considered for future studies to allow for the comparison of physiological, perceptual and performance measures. Furthermore, a repeat trial should be considered to determine the reliability of the responses.
5. The current study used 17 Rhodes University and Country Districts cricketers. Future investigations should use a larger, more homogenous sample of high calibre players (elite players) to increase the validity of the findings. Furthermore, the work-bout was designed using time motion analyses from international matches, the running requirements of which are very different from those performed by university batsmen.
6. Future studies should consider the implementation of intervention strategies to improve batting performance by enhancing the players' ability to cope with the game from a physical perspective.
7. Although there were indicators that the players were physically fatigued, future research should also look at the cognitive aspect of batting for extended periods of time.
8. Future research should control what the players eat before performing the protocol to determine what effect pre-exercise diet has on physiological, perceptual and performance responses.

PRACTICAL SIGNIFICANCE

Batsmen appear to experience physical fatigue after batting for extended periods of time. This is shown by an increase in sprint times from stage two to stage six.

However, this does not appear to translate to decrements in cognitive function as accuracy improved initially and then remained remarkably constant thereafter. It is therefore important that batsmen are trained from a physical point of view, in order to cope with the demands of extended batting requiring repeated sprints between the wickets. This can be done by implementing scientifically based training programs based on the findings of intervention studies.

The need for training programs that simulate real match situations is a highly important finding. The intensities that players execute in practice settings need to mimic the demands that players are faced with in real match-play. More specifically, players need to be trained according to situations they will be faced with in a match. For example, most training involves batting in the nets for short time periods without any running between the wickets. Batsmen should be running between the wickets at high intensities during a practice to simulate the demands of a high scoring ODI or Twenty/20 match. In this light, the BATEX[®] protocol would be a very useful protocol to use as different stages can be isolated and used as a training tool depending on specific requirements.

This physical training is further emphasized by the nature of the physiological and perceptual responses of the protocol. As such, it is evident that batting is not physiologically undemanding as it was previously thought to be. Therefore, there needs to be the development of a standardised battery of tests that can be used to increase the physical state of the modern cricketer. These tests need to be practical and they need to be able to be performed anywhere. Further, the importance of incorporating ratings of perceived effort in training cannot be overlooked as perceptions of effort increased with time and mimicked the decrements in sprint times.

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APPENDIX A: GENERAL INFORMATION

ETHICAL APPROVAL

INFORMATION TO PLAYERS

PLAYER CONSENT FORM

PHYSICAL ACTIVITY SCREENING QUESTIONNAIRE

PRE-TEST INSTRUCTIONS TO PLAYERS

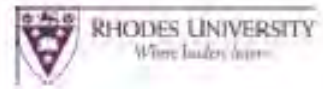
EQUIPMENT CHECKLIST

WARM-UP

ETHICAL APPROVAL



Human Kinetics and Ergonomics Application for Ethical Approval



Student Name: Lee Pote
Type of Research: Masters Research Project
Project Title: Selected physiological and perceptual responses of batsmen during a simulated one day international century: impact on performance
Supervisor: Dr Candice Christie
Report compiled: 28 September 2011

Dear Lee

Your application has been approved and the reviewers have suggested that you implement their suggested changes and take into consideration some of their suggestions.

Approved	Approved, on condition that suggestions have been effected ✓	Request for rework and resubmission	Rejected
----------	--	-------------------------------------	----------

Signed

A handwritten signature in cursive script, appearing to read "CJ Christie".

Dr CJ Christie
Chair: Human Kinetics and Ergonomics Ethics Committee

INFORMATION TO PLAYERS



HUMAN KINETICS AND ERGONOMICS

Contact information:

Name: Lee Pote

Cell number: 072 11 700 41

E-mail: g06p1630@campus.ru.ac.za

Dear _____

Thank you for volunteering to participate in the masters research that I am currently conducting. Your help and participation is greatly appreciated.

TITLE OF THESIS

Selected physiological and perceptual responses of batsmen during a simulated one day international century: impact on performance

AIMS OF THE STUDY

The game of cricket has been under researched to a large extent and most of the research that has been conducted has been on bowlers and the injuries that occur due to bowling. There have however been a limited amount of studies that have focused on the physiological demands of batsmen as well as the injuries that occur in batting, however these studies have only looked at responses over short periods of time. To date there have been no in-depth analyses of the physiological responses of batsmen batting for extended periods of time (for example, scoring a

century). Furthermore, the impact that these responses have on performance have not been considered. Therefore the main aim of this study is to determine the effect that an expected increased physiological load during a century has on performance. Through this, it may be possible to implement specific and scientifically based training programs to improve performance and reduce the risk of injury.

PLAYER POOL

All players selected for this study are males between the ages of 18 and 30 years old, and are currently playing professional or semi-professional cricket. Only those players batting at or higher than six on the batting line-up were considered, due to the nature of the study.

TESTING SESSIONS

Testing will take place at the Kingswood College indoor sports centre in Grahamstown. The study will consist of two sessions:

Session 1: habituation and collection of baseline data

The duration of this session will be approximately 30 minutes.

The purpose of session 1 is:

- Explain the study
- To collect basic demographic and anthropometric data
- To sign informed consent
- To complete the physical activity screening questionnaire
- To familiarise the player with the equipment to be used
- To explain and habituate the player to the batting protocol
- To determine a suitable slot/time to perform the test protocol

The following demographic and anthropometric data will be collected at the first testing session:

Stature

Mass

% Body Fat (using skinfold measures)

Age

Session 2: experimental session

The duration of this session will be approximately 2 hours and 30 minutes.

During this session players will be required to perform a batting protocol (BATEX[®]) that simulates scoring a one day international century. The BATEX[®] protocol consists of six stages (5 overs each) and is typical of scoring a one day international century. Stages 1, 3 and 5 completed at the participants self-selected pace while stages 2, 4 and 6 are completed at an all-out intensity sprint. Between each delivery players are allowed a 35 second break and between each over an 80 second break. Players are also allowed a 2 minute 30 second break at the end of each stage and a 4 minute break at the halfway point of the protocol. At the end of each over and at the end of each stage physiological, performance and perceptual responses will be measured and recorded.

Testing will occur during the months of _____ and _____. Due to equipment constraints, each subject will be tested during separate time slots. The following physiological, perceptual and performance data will be collected during this testing session:

Physiological data: Heart rate

Oxygen uptake

Energy expenditure

Core temperature

Perceptual data: Ratings of perceived exertion

Performance measures: Accuracy (of impact of ball on bat)

Sprint time between wickets (only during stages 2, 4 and 6)

The physiological responses will be assessed by heart rate (HR), oxygen uptake (VO₂), energy expenditure (EE) and core temperature (T_c), while the perceptual

responses will be monitored with the use of Borg's (1998) ratings of perceived exertion (RPE) scale. The performance responses will be assessed using an accuracy measure (accuracy of the impact of the ball on the bat) as well as sprint time between the wickets (during stages 2, 4 and 6).

RISKS

The risks of this study are fairly minimal and are the same as batting during a normal cricket match. However, there may be a risk of some slip, trip and fall accidents and pulled muscles due to all out sprinting during some stages of the protocol. There is also a risk of fatigue and cramp due to the long duration of the protocol. Before testing occurs a warm-up session with cricket-specific exercises will be conducted to avoid such injuries from occurring. The mask of the k_4b^2 metabolic system may impair vision, but players will be habituated to the equipment before testing. The core temperature pills used to measure core body temperature do exhibit some contraindications, but a list of these contraindications will be given to each player before the pill is administered, and if players match any of the criteria they will be withdrawn from the study. There will also be drinks breaks throughout the protocol where players will be allowed to take in water. The information obtained from the study will be handled in the strictest confidence and if the physical activity screening questionnaire is filled out honestly and precisely, then the risks associated with this study are very limited. The physiological responses of each player will also be monitored throughout the protocol and if these responses reach dangerously elevated levels, then the test will be terminated immediately.

BENEFITS

Feedback from the study will be provided for each player. This should help players to better understand the physiological demands placed on the body when batting for extended periods of time such as scoring a one day international century. These demands may also help with implementing better pacing strategies when scoring a century and the development of training programs may help in improving overall batting performance and player fitness. The more 'fit' or well trained a player is means that players become less fatigued and therefore do not lose concentration and can focus on improving performance during batting.

OTHER

If there are any queries or questions please do not hesitate to contact me at any time (contact details above). Photographs may be taken for illustration purposes, but these will remain anonymous. Player anonymity will be protected in the form of coding and names will not be released to any people other than the researcher and their supervisor. If at any time players feel the need to withdraw from the study due to personal reasons, they may do so without any consequence or action.

PHYSICAL ACTIVITY SCREENING QUESTIONNAIRE

Name: _____

Code: _____

MEDICAL HISTORY

Tick any of the following conditions, diseases or disorders that you have had in the past or are presently being treated for by a physician or health professional.

- | | | |
|--|------------------------------------|--|
| <input type="checkbox"/> Heart problems | <input type="checkbox"/> Anaemia | <input type="checkbox"/> Eye problems |
| <input type="checkbox"/> Peripheral vascular disorders | <input type="checkbox"/> Asthma | <input type="checkbox"/> Hypoglycaemia |
| <input type="checkbox"/> High/low blood pressure | <input type="checkbox"/> Emphysema | <input type="checkbox"/> Diabetes |
| <input type="checkbox"/> Epilepsy | <input type="checkbox"/> Migraine | <input type="checkbox"/> Hyperthyroidism |
| <input type="checkbox"/> Other (specify): _____ | | |

Have you had any recent medical problems? If so give details below:

Are you currently suffering from any orthopaedic disorder problem? If so briefly describe the problem:

Are there any other concerns, medical or otherwise, that you feel are worth mentioning:

Please indicate any prescribed or over the counter medication that you are currently taking or have taken in the past 6 months:

OTHER HABITS

Please tick appropriate box:

Do you smoke?

YES	NO
-----	----

 If Yes, how many cigarettes per day: _____

EXERCISE HISTORY

Do you exercise regularly?

YES	NO
-----	----

How many days per week do you normally spend performing at least 20 minutes of moderate to strenuous exercise:

1	2	3	4	5	6	7	0
---	---	---	---	---	---	---	---

Do you experience shortness of breath or chest discomfort with exercise?

YES	NO
-----	----

Provide a rough average of the number of organised/scheduled physical activity sessions you participate in during the week. Tick the appropriate block(s) and fill the number of sessions in next to the particular activity:

- Jogging_____
- Hockey_____
- Rowing_____
- Swimming_____
- Tennis_____
- Rugby_____
- Cricket_____
- Soccer_____
- Squash_____
- Other_____

PRE-TEST INSTRUCTIONS TO PLAYERS

Please fill in all forms and questionnaires as accurately as possible to avoid any risk of injury or damage. If you have any serious medical problems or illnesses, please can you disclose them to the researcher in order to ensure your well being. Please can these instructions also be followed to the best of your ability so that the results obtained from the study are as accurate as possible. Your help is greatly appreciated.

24 hours before testing

- No alcohol is to be consumed
- Do not partake in any strenuous physical activity (light exercise to 'loosen up' is permitted)
- No medication is to be taken unless absolutely necessary (if medication is taken, please inform the researcher)
- Normal eating habits and fluid intake is to be maintained (except alcohol)
- A good nights sleep is recommended

Day of testing

- Reminder: please bring full cricket kit as well as your white flannels and t-shirt
- It is important to eat a good breakfast
- Consume a light meal before testing (at least an hour before performing the protocol).
- Use the bathroom facilities before testing starts
- **NB:** Swallow the core body temperature pill with a large glass of water 2 hours before performing the protocol

EQUIPMENT CHECKLIST

- Harpenden stadiometer
- LifeMax electronic scale
- Harpenden skinfold caliper
- k4b² portable metabolic system
- Polar[®] heart rate monitor strap
- CoreTemp[®] monitoring system and pills
- Ratings of perceived exertion scale
- LED sensors and timing device
- Electronic bat
- Data collection sheets
- Computers x 2

WARM-UP (Houghton *et al.*, 2011)

4 min 20m shuttle running

- 1 min jogging (50%)
- 1 min striding (70%)
- 1 min jogging (50%)
- 1 min striding (70%)

5 min dynamic stretching

- 2x 20m lunges
- 2x 20m side to side skips
- 20m heel kicks
- 2x 20m skipping
- 20m open the gate dynamic stretching
- 20m close the gate dynamic stretching
- 20m dynamic hamstring stretch
- 3x “run a two” at 80% effort

APPENDIX B: DATA COLLECTION

RATINGS OF PERCEIVED EXERTION (RPE) SCALE

RPE EXPLANATION SHEET

DATA COLLECTION SHEETS:

Anthropometric and demographic data

Physiological and perceptual responses

Sprint time data

RATINGS OF PERCEIVED EXRTION SCALE

Borg's RPE Scale	
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (Heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Borg RPE scale
© Gunnar Borg, 1970, 1985, 1994, 1998

RPE EXPLANATION SHEET

You are going to be taking part in a simulated batting work-bout which is typical of scoring a one day international century. The protocol consists of 6 stages (5 overs each) during which you will be required to complete a number of shuttle runs depending on the type of shot played as well as the 'field settings' for that stage of the protocol. During the work-bout, at set intervals throughout, various physiological and perceptual data will be collected. Some of these measures will require you, as a player, to estimate how hard the activity that you are performing is. In other words you will have to rate the level of exertion you are feeling. For this you will be asked to point to a number on a scale which corresponds to how hard you are exerting yourself in terms of your cardiovascular system (your heart and lungs). This rating should be as objective as possible and you should try not to underestimate or overestimate your level of exertion.

The RPE scale is a graded rating scale that ranges from a minimum of 6 or "very, very light" to a maximum of 20 or "very, very hard". So, a rating of 6 would mean that you are standing still and not exerting yourself, whereas a rating of 20 would mean that you are exerting yourself maximally. You will be asked to identify the level of exertion that you perceive after every over as well as after every stage of the protocol. This rating should be as accurate as possible.

DATA COLLECTION SHEETS

Anthropometric and demographic data

Name: _____

Stature: _____

Code: _____

Mass (before): _____ (after) _____

Age: _____

BMI: _____

Current team represented: _____

Highest team represented at schoolboy level: _____

Years of cricketing experience: _____

Percentage body fat

Triceps: _____

Abdominal: _____

Chest: _____

Thigh: _____

Subscapular: _____

Axilla: _____

Suprailliac: _____

%BF: _____

Physiological and perceptual responses

Participant _____		Code _____						Notes
Date _____	Resting HR _____	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	
Overs Simulated	Time (min:s)							
0.1	00:30	1,1	1,1	-	1,1,4	1,3	1,1,3,4	
0.2	01:05							
0.3	01:40							
0.4	02:15							
0.5	02:50							
0.6	03:25							
1.1	HR							
	Tc							
	RPE							
	04:45	-	1,1,2	1	1,1,2	1,1,2	1,1,2,4	
1.2	05:20							
1.3	05:55							
1.4	06:30							
1.5	07:05							
1.6	07:40							
	HR							
	Tc							
	RPE							
2.1	09:00	1,1,2	1,1,4	1,4	1,1,4	1,1,4	1,1,4,1	
2.2	09:35							
2.3	10:10							
2.4	10:45							
2.5	11:20							
2.6	11:55							
3.1	HR							
	Tc							
	RPE							
	13:15	1,4	1,1,2	2,3	1,1,2,3	1,1,2	1,1,2	
3.2	13:50							
3.3	14:25							
3.4	15:00							
3.5	15:35							
3.6	16:10							
	HR							
	Tc							
	RPE							

4.1	17:30	1,4	1,1,4	1,4	1,1,4	1,1,4	1,1, 2,4
4.2	18:05						
4.3	18:40						
4.4	19:15						
4.5	19:50						
4.6	20:25						
	HR						
	Tc						
	RPE						

Sprint time data

DATA COLLECTION SHEET- SPRINT TIMES BETWEEN WICKETS

Stage 2	Time (s)
Run 1	
Run 2	

Stage 4	Time (s)
Run 1	
Run 2	

Stage 6	Time (s)
Run 1	
Run 2	
Run 3	

APPENDIX C: SUMMARY REPORTS

STATISTICAL ANALYSES

STATISTICAL ANALYSES

Heart rate

Tukey HSD test; variable DV_1 (Heart rate) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 48.390, df = 80.000							
Cell No.	HR	{1}	{2}	{3}	{4}	{5}	{6}
		124.16	148.92	136.25	150.53	144.12	159.61
1	Stage 1		0.000125	0.000156	0.000125	0.000125	0.000125
2	Stage 2	0.000125		0.000136	0.983977	0.346322	0.000457
3	Stage 3	0.000156	0.000136		0.000125	0.017594	0.000125
4	Stage 4	0.000125	0.983977	0.000125		0.089198	0.003716
5	Stage 5	0.000125	0.346322	0.017594	0.089198		0.000125
6	Stage 6	0.000125	0.000457	0.000125	0.003716	0.000125	

Breathing frequency

Tukey HSD test; variable DV_1 (Rf) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 3.2808, df = 75.000							
Cell No.	RF	{1}	{2}	{3}	{4}	{5}	{6}
		30.874	36.071	34.584	38.956	38.590	42.295
1	Stage 1		0.000126	0.000128	0.000126	0.000126	0.000126
2	Stage 2	0.000126		0.198472	0.000455	0.002575	0.000126
3	Stage 3	0.000128	0.198472		0.000126	0.000127	0.000126
4	Stage 4	0.000126	0.000455	0.000126		0.992610	0.000145
5	Stage 5	0.000126	0.002575	0.000127	0.992610		0.000128
6	Stage 6	0.000126	0.000126	0.000126	0.000145	0.000128	

Tidal volume

Tukey HSD test; variable DV_1 (VT) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .01347, df = 75.000							
Cell No.	VT	{1}	{2}	{3}	{4}	{5}	{6}
		1.5068	1.7535	1.3989	1.7877	1.3951	1.7270
1	Stage 1		0.000127	0.102748	0.000126	0.082627	0.000136
2	Stage 2	0.000127		0.000126	0.960228	0.000126	0.987282
3	Stage 3	0.102748	0.000126		0.000126	0.999999	0.000126
4	Stage 4	0.000126	0.960228	0.000126		0.000126	0.679298
5	Stage 5	0.082627	0.000126	0.999999	0.000126		0.000126
6	Stage 6	0.000136	0.987282	0.000126	0.679298	0.000126	

Minute ventilation

Tukey HSD test, variable DV_1 (VE) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 16.049, df = 75.000							
Cell No.	VE	{1}	{2}	{3}	{4}	{5}	{6}
		45.833	63.308	48.101	69.256	53.231	72.438
1	Stage 1		0.000126	0.600424	0.000126	0.000144	0.000126
2	Stage 2	0.000126		0.000126	0.001102	0.000126	0.000126
3	Stage 3	0.600424	0.000126		0.000126	0.006875	0.000126
4	Stage 4	0.000126	0.001102	0.000126		0.000126	0.229182
5	Stage 5	0.000144	0.000126	0.006875	0.000126		0.000126
6	Stage 6	0.000126	0.000126	0.000126	0.229182	0.000126	

Oxygen uptake

Tukey HSD test, variable DV_1 (VO2) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 7.0091, df = 80.000							
Cell No.	VO2	{1}	{2}	{3}	{4}	{5}	{6}
		29.289	38.683	31.318	41.773	35.378	43.429
1	Stage 1		0.000125	0.233978	0.000125	0.000125	0.000125
2	Stage 2	0.000125		0.000125	0.013009	0.006320	0.000141
3	Stage 3	0.233978	0.000125		0.000125	0.000473	0.000125
4	Stage 4	0.000125	0.013009	0.000125		0.000125	0.456857
5	Stage 5	0.000125	0.006320	0.000473	0.000125		0.000125
6	Stage 6	0.000125	0.000141	0.000125	0.456857	0.000125	

Carbon dioxide production

Tukey HSD test, variable DV_1 (VCO2) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 55051, df = 80.000							
Cell No.	VCO2	{1}	{2}	{3}	{4}	{5}	{6}
		2155.5	2854.9	2133.2	3019.7	2340.2	3056.9
1	Stage 1		0.000125	0.999797	0.000125	0.208281	0.000125
2	Stage 2	0.000125		0.000125	0.325490	0.000125	0.133709
3	Stage 3	0.999797	0.000125		0.000125	0.116529	0.000125
4	Stage 4	0.000125	0.325490	0.000125		0.000125	0.997325
5	Stage 5	0.208281	0.000125	0.116529	0.000125		0.000125
6	Stage 6	0.000125	0.133709	0.000125	0.997325	0.000125	

Respiratory exchange ratio

Tukey HSD test; variable DV_1 (RQ) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .00112, df = 80.000							
Cell No.	RQ	{1}	{2}	{3}	{4}	{5}	{6}
		.95391	.94745	.86496	.91968	.84004	.88584
1	Stage 1		0.993179	0.000125	0.042646	0.000125	0.000126
2	Stage 2	0.993179		0.000125	0.162364	0.000125	0.000133
3	Stage 3	0.000125	0.000125		0.000238	0.262875	0.460246
4	Stage 4	0.042646	0.162364	0.000238		0.000125	0.046658
5	Stage 5	0.000125	0.000125	0.262875	0.000125		0.002067
6	Stage 6	0.000126	0.000133	0.460246	0.046658	0.002067	

Energy expenditure

Tukey HSD test; variable DV_1 (EE) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 1.2095, df = 80.000							
Cell No.	EE	{1}	{2}	{3}	{4}	{5}	{6}
		11.486	15.182	12.101	16.281	13.588	16.904
1	Stage 1		0.000125	0.581131	0.000125	0.000128	0.000125
2	Stage 2	0.000125		0.000125	0.050748	0.000969	0.000371
3	Stage 3	0.581131	0.000125		0.000125	0.002403	0.000125
4	Stage 4	0.000125	0.050748	0.000125		0.000125	0.567288
5	Stage 5	0.000128	0.000969	0.002403	0.000125		0.000125
6	Stage 6	0.000125	0.000371	0.000125	0.567288	0.000125	

Core temperature

Tukey HSD test; variable DV_1 (Tc) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .12538, df = 60.000							
Cell No.	TC	{1}	{2}	{3}	{4}	{5}	{6}
		37.650	38.211	38.390	38.154	38.477	38.718
1	Stage 1		0.002142	0.000151	0.007468	0.000134	0.000133
2	Stage 2	0.002142		0.792196	0.998502	0.405724	0.007122
3	Stage 3	0.000151	0.792196		0.540807	0.988675	0.185700
4	Stage 4	0.007468	0.998502	0.540807		0.202028	0.002040
5	Stage 5	0.000134	0.405724	0.988675	0.202028		0.513102
6	Stage 6	0.000133	0.007122	0.185700	0.002040	0.513102	

Ratings of perceived exertion

Tukey HSD test; variable DV_1 (RPE) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 1.1614, df = 80.000							
Cell No.	RPE	{1}	{2}	{3}	{4}	{5}	{6}
		8.6353	12.447	10.741	14.047	12.188	16.035
1	Stage 1		0.000125	0.000127	0.000125	0.000125	0.000125
2	Stage 2	0.000125		0.000324	0.000708	0.981460	0.000125
3	Stage 3	0.000127	0.000324		0.000125	0.002625	0.000125
4	Stage 4	0.000125	0.000708	0.000125		0.000161	0.000133
5	Stage 5	0.000125	0.981460	0.002625	0.000161		0.000125
6	Stage 6	0.000125	0.000125	0.000125	0.000133	0.000125	

Sprint time

Tukey HSD test; variable DV_1 (Sprint time) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .05123, df = 32.000				
Cell No.	SPRINT	{1}	{2}	{3}
		5.6141	5.6741	5.8147
1	Stage 2		0.722670	0.037837
2	Stage 4	0.722670		0.182279
3	Stage 6	0.037837	0.182279	

Accuracy

Tukey HSD test; variable DV_1 (Accuracy) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 295.16, df = 65.000							
Cell No.	ACC	{1}	{2}	{3}	{4}	{5}	{6}
		104.64	67.313	67.299	58.833	62.615	61.212
1	Stage 1		0.000133	0.000133	0.000130	0.000130	0.000130
2	Stage 2	0.000133		1.000000	0.780830	0.978435	0.934736
3	Stage 3	0.000133	1.000000		0.781973	0.978708	0.935319
4	Stage 4	0.000130	0.780830	0.781973		0.991918	0.999149
5	Stage 5	0.000130	0.978435	0.978708	0.991918		0.999939
6	Stage 6	0.000130	0.934736	0.935319	0.999149	0.999939	