MUSCULOSKELETAL AND PERCEPTUAL RESPONSES OF BATSMEN COMPARING HIGH- AND MODERATE-VOLUME SPRINTS BETWEEN THE WICKETS

BY

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ABSTRACT

Background: Literature has associated repeated eccentric muscle actions with increased muscle damage of the muscles involved. Eccentric actions are typical in sports which are 'stop-start' in nature requiring rapid acceleration and deceleration, typical of a batting activity in cricket. Ultra-structural damage of the skeletal muscle as a consequence of repeated decelerating activities is associated with performance decrements, particularly muscle strength and sprinting speeds. This suggests that eccentric strength decrements may provide an indication for the development of muscle strain injuries during these activities. Despite these findings, limited research has identified the specific musculoskeletal demands placed on cricket batsmen, particularly with reference to various match intensities.

Objective: The present study, therefore, sought to determine the specific musculoskeletal, physiological and perceptual demands placed on specialised batsmen during two work bouts of different intensities; one representing a high-intensity work bout and the other a moderate-intensity work bout. The dependent variables of interest were muscle activation, isokinetic strength changes, heart rate, 'central' and 'local' ratings of perceived exertion (RPE), body discomfort and performance.

Methods: The two experimental conditions, representative of a high- (HVR) and moderate-volume running (MVR) batting protocol, required players to perform a simulated batting work bout of either twelve or six runs an over, within a laboratory setting. Selected physiological, perceptual and performance measures were collected at specific time intervals throughout the work bout while the biophysical measures were collected prior to, and following both protocols.

Results: Of the variables measured, heart rate, 'central' and 'local' RPE values were observed to increase significantly ($p<0.05$) over time. This increase was greater as a consequence of the HVR in comparison to the MVR. No change in sprint times was documented during the MVR, in contrast, significant ($p<0.05$) increases over time were observed during the HVR, further highlighting the elevated demands associated with this condition. In addition, an 'end spurt' was observed particularly following the HVR condition, suggesting athletes were conserving themselves through the adoption of a pacing strategy. Reductions in biceps femoris and semitendinosus muscle activation levels were observed following the HVR. This was further supported by the significantly greater levels of semitendinosus activation following the MVR when compared to the HVR. Peak concentric and eccentric knee extensor (EXT) (-17.17% and -16.07% respectively) and eccentric flexor (FLEX) (-17.49%) values decreased significantly ($p<0.05$) following the HVR at 60°.s^{-1}. In addition, concentric and eccentric total work produced by the flexors and eccentric extensors resulted in significantly ($p<0.05$) lower values due to the HVR.

Conclusion: The intermittent high-volume batting work bout elicited elevated mean heart rates, perceived ratings of cardiovascular and muscular effort and sprint times. Furthermore, hamstring activation levels and muscle strength, particularly concentric strength of the dominant lower limb were negatively affected by the HVR condition. These results suggest elevated demands were placed on the hamstring musculature as a consequence of the HVR condition, indicating a greater degree of musculoskeletal strain and increased injury risk associated with running between the wickets at this intensity, representative of an aggressive batting scenario.

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CHAPTER I

INTRODUCTION

BACKGROUND TO THE STUDY

Continuous or steady-state activities, such as long distance running, have been the focus of many investigations (Drust *et al*., 2000 and Christie *et al*., 2008). In contrast however, literature involving activities of an intermittent nature, such as cricket, soccer, hockey and rugby have been rather limited (Morris *et al*., 1998; Drust *et al*., 2000; Spencer *et al*., 2004; Duffield and Drinkwater, 2008). Cricket is an intermittent sport characterised by repeated start-stop activities during a continuous period of play. Due to the highly unpredictable nature of the match, laboratory investigations are difficult and this has resulted in a limited amount of literature available on the demands of the sport (Drust *et al*., 2000). Despite an increase in the volume of cricket-related research in the recent past, there are still numerous aspects of the match in need of investigation.

Unpredictable periods of batting, as well as repeated high-intensity sprinting between the wickets leave batsmen vulnerable to injuries due to impact, or at a soft tissue level (Stretch, 1993; Stretch, 2003; Stretch and Venter, 2005; Stretch and Raffan, 2011). There is therefore a need to focus on each aspect of the match, these being bowling, fielding and batting, in order to enhance training, improve performance, and therefore minimise the number of injuries presented by each player. During an innings, batsmen are required to sprint, rapidly decelerate and accelerate as well as change direction repeatedly between the wickets which are set 17.68 meters apart. These activities result in repeated eccentric and concentric muscle actions within the lower limb musculature, but particularly within that of the quadriceps and hamstrings (Bennell *et al*., 1998; Whitehead *et al*., 1998; Clark, 2008). During these movements, antagonistic muscles counteract the movement brought about by the agonistic muscles during deceleration activities; thereby function to control the load of the involved muscles (Friden *et al*., 1983; Byrne and Eston, 2002). This control has been associated with strength, power and speed reductions which are indicative of fatigue and an elevated injury risk (Friden *et al*., 1981; Friden *et al*., 1983; Byrne and Eston, 2002; Highton *et al*., 2009). Eccentric muscle activity refers to the simultaneous contraction and lengthening of the muscle (Whitehead *et al*., 1998), excessive eccentric loading is associated with impaired muscle structure, function and metabolism, leading to ultra-structural damage of the skeletal muscle (Byrne and Eston, 2002 and Highton *et al*., 2009). Recent literature has identified both immediate and prolonged decreases in sprinting speed, muscular strength and agility with activities requiring repeated eccentric actions, resulting in reductions in performance (Highton *et al*., 2009). Further, it is apparent that muscle strains are most prevalent during the eccentric phase of a movement (Pull and Ranson, 2007). It can therefore be inferred that batsmen are most susceptible to muscular strain injuries during the rapid deceleration phase of running between the wickets.

In other intermittent sports such as rugby union, results within our laboratory have shown no strength changes in the quadriceps musculature yet significant reductions in hamstring muscle strength as a consequence of the intermittent activity profile (Christie and Brown, 2009). Further, there was a decline in hamstring muscle activity over time following simulated rugby union activity (Christie and Brown, 2009) which is an indication of fatigue, which in itself, increases susceptibility of the hamstring musculature to muscular strain or injury (Christie and Brown, 2009). Further pilot research in our laboratory has further identified a significant reduction in eccentric muscle strength following a batting work bout of six runs per over, indicating the onset of fatigue and an additional injury risk increase (Christie *et al*., 2011b).

It has been suggested that the musculoskeletal and physiological demands placed on batsmen are directly associated with the duration of activity participation (Enoka, 1995). However, the intensity of the shorter match formats are known to be greater than those observed during multiple-day matches, particularly during the last overs of one-day cricket (last fifteen overs) (Noakes and Durandt, 2000; Christie *et al*., 2008; Houghton, 2010; Petersen *et al*., 2010). The intensity of one-day matches are determined by the run total and matches of a higher intensity have been classified as a run total of a minimum of 260, and present record of 438, equating to a respective mean of 5.2 or 8.56 runs per over. Woolmer and Noakes (2008) suggested that four runs per over (rpo) was a very conservative run rate when looking at the modern match of cricket, and recommended that twelve rpo was a more accurate high scoring run rate during the final stages of an innings, further supported by Petersen *et al*. (2010). Furthermore, calculations involving peak physical activity of batsmen scoring a century during one-day cricket resulted in a mean running speed of 24km.h^{-1}, with a minimum of 110 decelerations (Noakes and Durandt, 2000 and Woolmer and Noakes, 2008). These values indicate increased musculoskeletal and physiological demands placed on batsmen during limited overs cricket. Furthermore, success in batting is associated with batting for increased periods of time (two hours or more) and during this time; batsmen must alter the selected batting strategy to an aggressive or defensive one, depending on the situation (Clarke and Norman, 1999 and Preston and Thomas, 2000). An aggressive strategy involves an increase in the number of runs scored through shot selection of greater risk and running. It is expected that an increase in the musculoskeletal, physiological and perceptual demands will likely occur with the more higher-intensity match situations; aggressive match formats requiring explosive bursts of speed, power and an increase in the number of rapid decelerations due to the increase in sprinting between the wickets.

It is believed that both a moderate- and high-volume of runs per over would increase these adverse effects. In order to increase the scientific understanding surrounding these demands, this study focused on the repeated eccentric demands placed on players due to the rapid acceleration and deceleration required to increase the run total, and the associated physiological and perceptual demands induced by this form of activity.

STATEMENT OF THE PROBLEM

Despite the advancements observed in the way that cricket is played, there has been limited research focusing on the demands induced by the repeated activity of sprinting between the wickets during batting. During repeated sprint activity, there is an increased risk of muscle strain injuries in the lower limb musculature.

Furthermore, there has been no recent literature comparing the differences in musculoskeletal and perceptual demands placed on batsmen during matches of a higher and a lower intensity, represented by differences in running between the wickets. This study therefore attempted to determine the changes in selected musculoskeletal and perceptual demands placed on batsmen over time by comparing a protocol of higher volume, to one of a lower volume run rate.

RESEARCH HYPOTHESIS

It was expected that the selected musculoskeletal, physiological and perceptual measures would be greater over time in the high-volume compared to the moderate-volume run rate condition. Furthermore, a greater reduction in the eccentric strength of the hamstring complex would be anticipated following the high-volume experimental condition.

STATISTICAL HYPOTHESES

MUSCULOSKELETAL HYPOTHESES

The dominant limb of each player was measured to determine the musculoskeletal demands induced by the protocols.

1. **Hypothesis 1**

a) **Hypothesis 1a:** Proposed there would be no change in muscle activity between the high-volume and the moderate-volume running condition.

Ho: $\mu MA_{HVR} = \mu MA_{MVR}$

Ha: $\mu MA_{HVR} \neq \mu MA_{MVR}$

b) **Hypothesis 1b:** Proposed that there would be no change in muscle activity pre and post repeated sprints between the wickets.

Ho: $\mu MA_{HVRPRE} = \mu MA_{MVRPRE} = \mu MA_{HVRPOST} = \mu MA_{MVRPOST}$

Ha: $\mu MA_{HVRPRE} \neq \mu MA_{MVRPRE} \neq \mu MA_{HVRPOST} \neq \mu MA_{MVRPOST}$

2. **Hypothesis 2**

a) **Hypothesis 2a:** Proposed that there will be no difference in the following concentric strength parameters at 60°.s^{-1} pre and post repeated sprints between the wickets and between conditions.

i. Peak torque

Ho: $\mu PT_{HVRPRE} = \mu PT_{MVRPRE} = \mu PT_{HVRPOST} = \mu PT_{MVRPOST}$

Ha: $\mu PT_{HVRPRE} \neq \mu PT_{MVRPRE} \neq \mu PT_{HVRPOST} \neq \mu PT_{MVRPOST}$

ii. Work

Ho: $\mu W_{HVRPRE} = \mu W_{MVRPRE} = \mu W_{HVRPOST} = \mu W_{MVRPOST}$

Ha: $\mu W_{HVRPRE} \neq \mu W_{MVRPRE} \neq \mu W_{HVRPOST} \neq \mu W_{MVRPOST}$

iii. Power

Ho: $\mu P_{HVRPRE} = \mu P_{MVRPRE} = \mu P_{HVRPOST} = \mu P_{MVRPOST}$

Ha: $\mu P_{HVRPRE} \neq \mu P_{MVRPRE} \neq \mu P_{HVRPOST} \neq \mu P_{MVRPOST}$

b) **Hypothesis 2b:** Proposed that there will be no change in the following eccentric strength parameters at 60°.s^{-1} pre and post repeated sprints between the wickets and between conditions.

i. Peak torque

Ho: $\mu PT_{HVRPRE} = \mu PT_{MVRPRE} = \mu PT_{HVRPOST} = \mu PT_{MVRPOST}$

Ha: $\mu PT_{HVRPRE} \neq \mu PT_{MVRPRE} \neq \mu PT_{HVRPOST} \neq \mu PT_{MVRPOST}$

ii. Work

Ho: $\mu W_{HVRPRE} = \mu W_{MVRPRE} = \mu W_{HVRPOST} = \mu W_{MVRPOST}$

Ha: $\mu W_{HVRPRE} \neq \mu W_{MVRPRE} \neq \mu W_{HVRPOST} \neq \mu W_{MVRPOST}$

iii. Power

Ho: $\mu P_{HVRPRE} = \mu P_{MVRPRE} = \mu P_{HVRPOST} = \mu P_{MVRPOST}$

Ha: $\mu P_{HVRPRE} \neq \mu P_{MVRPRE} \neq \mu P_{HVRPOST} \neq \mu P_{MVRPOST}$

c) **Hypothesis 2c:** Proposed that there will be no difference in the following concentric strength parameters at 270°.s^{-1} pre and post repeated sprints between the wickets and between conditions.

i. Peak torque

Ho: $\mu PT_{HVRPRE} = \mu PT_{MVRPRE} = \mu PT_{HVRPOST} = \mu PT_{MVRPOST}$

Ha: $\mu PT_{HVRPRE} \neq \mu PT_{MVRPRE} \neq \mu PT_{HVRPOST} \neq \mu PT_{MVRPOST}$

ii. Work

Ho: $\mu W_{HVRPRE} = \mu W_{MVRPRE} = \mu W_{HVRPOST} = \mu W_{MVRPOST}$

Ha: $\mu W_{HVRPRE} \neq \mu W_{MVRPRE} \neq \mu W_{HVRPOST} \neq \mu W_{MVRPOST}$

iii. Power

Ho: $\mu P_{HVRPRE} = \mu P_{MVRPRE} = \mu P_{HVRPOST} = \mu P_{MVRPOST}$

Ha: $\mu P_{HVRPRE} \neq \mu P_{MVRPRE} \neq \mu P_{HVRPOST} \neq \mu P_{MVRPOST}$

d) **Hypothesis 2d:** Proposed that there will be no change in the following eccentric strength parameters at 270°.s^{-1} pre and post repeated sprints between the wickets and between conditions.

i. Peak torque

Ho: $\mu PT_{HVRPRE} = \mu PT_{MVRPRE} = \mu PT_{HVRPOST} = \mu PT_{MVRPOST}$

Ha: $\mu PT_{HVRPRE} \neq \mu PT_{MVRPRE} \neq \mu PT_{HVRPOST} \neq \mu PT_{MVRPOST}$

ii. Work

Ho: $\mu W_{HVRPRE} = \mu W_{MVRPRE} = \mu W_{HVRPOST} = \mu W_{MVRPOST}$

Ha: $\mu W_{HVRPRE} \neq \mu W_{MVRPRE} \neq \mu W_{HVRPOST} \neq \mu W_{MVRPOST}$

iii. Power

Ho: $\mu P_{HVRPRE} = \mu P_{MVRPRE} = \mu P_{HVRPOST} = \mu P_{MVRPOST}$

Ha: $\mu P_{HVRPRE} \neq \mu P_{MVRPRE} \neq \mu P_{HVRPOST} \neq \mu P_{MVRPOST}$

PHYSIOLOGICAL HYPOTHESIS

3. **Hypothesis 3:** Proposed that there will be no change in heart rate responses between conditions and over time.

Ho: $\mu MA_{HVR1} = \mu MA_{MVR1} = \mu MA_{HVR2} = \mu MA_{MVR2} = ... = \mu MA_{HVRn} = \mu MA_{MVRn}$

Ha: $\mu MA_{HVR1} \neq \mu MA_{MVR1} \neq \mu MA_{HVR2} \neq \mu MA_{MVR2} \neq ... \neq \mu MA_{HVRn} \neq \mu MA_{MVRn}$

PERCEPTUAL HYPOTHESIS

4. **Hypothesis 4:** Proposed that there will be no change in perceptual measures (‘central’ and ‘local’ ratings of perceived effort) between conditions and over time.

Ho : $\mu PER_{HVR1} = \mu PER_{MVR1} = \mu PER_{HVR2} = \mu PER_{MVR2} = \ldots = \mu PER_{HVRn} = \mu PER_{MVRn}$

Ha : $\mu PER_{HVR1} \neq \mu PER_{MVR1} \neq \mu PER_{HVR2} \neq \mu PER_{MVR2} \neq \ldots \neq \mu PER_{HVRn} \neq \mu PER_{MVRn}$

PERFORMANCE HYPOTHESIS

5. **Hypothesis 5:** Proposed that there will be no change in performance measures between conditions and over time.

Ho : $\mu PERF_{HVR1} = \mu PERF_{MVR1} = \mu PERF_{HVR2} = \mu PERF_{MVR2} = \ldots = \mu PERF_{HVRn} = \mu PERF_{MVRn}$

Ha : $\mu PERF_{HVR1} \neq \mu PERF_{MVR1} \neq \mu PERF_{HVR2} \neq \mu PERF_{MVR2} \neq \ldots \neq \mu PERF_{HVRn} \neq \mu PERF_{MVRn}$

Where:

- MA = Muscle Activity
- PT = Peak Torque
- W = Work
- P = Power
- HR = Heart Rate
- PER = Perceptual Demands (Rating of Perceived Exertion and Body Discomfort scale)
- PERF = Performance measures (double shuttle sprint times)
- HVR = High-volume running
- MVR = Moderate-volume running
- 1-n = Respective overs
- PRE = Before high- or moderate-volume running conditions
- POST = After high- or moderate-volume running conditions
- 6, 12-n = Specific speeds (6, 12, 15, 21km.h^{-1})

DELIMITATIONS

The study was delimited to 20 male cricket players between the ages 18 to 35 years. Half the players included sub-elite or elite cricketers comprising the top five in the batting order from the Eastern Cape Province of South Africa. Those that remained were specialist batsmen from the first XV Rhodes University cricket squad. The primary focus of the study was to compare a high- and a moderate-volume sprint work-load between the wickets using measures of musculoskeletal, physiological and perceptual responses. Each player was required to perform two protocols simulating both a high- and a moderate-intensity one-day cricket match, represented by varying volumes of running (six compared to twelve shuttle sprints).

All testing occurred under standardised conditions within a laboratory setting. Players were required to attend three sessions in order to fulfil the requirements of the study. The first session allowed for a thorough explanation of the study both verbally and in writing. Specific requests regarding the 24 hours prior to testing were explained to the players. Demographic data including age, body mass and stature, along with injury history was obtained. Further baseline measures included body fat percentage (skinfolds) and reference heart rate. Injury history data allowed for the exclusion of any player presenting with a musculoskeletal injury of the lower limb or back in the previous six months. All players, no matter the experience, were habituated to all equipment used in both conditions, particularly to both the Cybex 6000 isokinetic dynamometer and the treadmill. The correct running technique to be adopted during treadmill running was explained, and all players were habituated to running at each speed as would be required in the protocol. Further habituation to the walkway within the laboratory, where the protocol was to be performed was ensured.

The second and third sessions involved the completion of either experimental condition; the order of execution was randomized in order for the results to be directly associated with the specific protocol. The dependent variables of the study included: muscle activity using electromyography, isokinetic peak torque, total work and average power, heart rate, both ‘central’ and ‘local’ ratings of perceived exertion, body discomfort, as well as performance using an LED system connected to a timer. A Pain Perception Scale (Appendix A, pg 131) was used to identify any presence of muscle soreness prior to experimentation; if soreness was identified, experimentation was postponed. Data collection for both conditions was identical and allowed for a direct comparison between results.

LIMITATIONS

Although a conscious effort was made to control all possible variables which may have influenced the results of the investigation, some of the following may have posed limitations to the study, and therefore must be taken into account when examining the results:

> This study was conducted within a laboratory setting, and as such was not able to incorporate all aspects of a cricket match, such as shot selection and varying environmental conditions (wind and sun exposure), as would occur in an *in situ* investigation.
>
> Despite all participants being part of an internal university cricket league, and select individuals forming part of the sub-elite category of the sport, the training status of each individual could not be controlled.
>
> Although all players were instructed not to eat a large meal three hours prior to testing, to not consume any alcohol or to participate in strenuous exercise 24 hours prior to both experimental sessions, this could not be controlled by the researcher. If any of the abovementioned activities had occurred and were revealed to the researcher when asked, testing was cancelled and postponed to another day.

Although the researcher made every effort to provide identical verbal motivation throughout both batting-specific work bouts, as well as during the muscle strength measures using isokinetic dynamometry, this may not have motivated all participants to provide an ‘all out’ effort, therefore resulting in variance within results.

Although player habituation to all equipment was ensured, as the length of the study increased in duration the wooden walkway upon which participants performed both work bouts became increasingly smoother, reducing the friction that was present at the onset of the investigation. This may have resulted in a slight alteration in the manner in which players performed the task, thereby increasing the variability in the results obtained.

The wooden walkway was in itself a limitation, as the surface is very different to that of a cricket pitch, resulting in possible variation in players’ running styles.

Electromyography analyses are influenced by electrode placement as well as by interference from surrounding muscles. Although every effort was made to attach electrodes in the same place during both testing sessions, electrodes falling off and being replaced during the work bout may have resulted in varying results, and this must be considered in the interpretation of the results.

During isokinetic strength measures, total work is highly dependent on the range of motion (ROM) during knee extensions. This was not rigidly controlled and may have resulted in varying ROM prior to, and following the work bout.

Players were informed on the requirements of both conditions, and this included knowledge of the end point. In a cricket match, batsmen are unable to predict the period of time spent at the crease and are therefore are less likely to adopt a pacing strategy. This may have influenced certain variables measured in the current study.

CHAPTER II

REVIEW OF RELATED LITERATURE

INTRODUCTION

The different stresses faced by the body during any form of exercise fall into three main categories; biomechanical, physiological and psychological, all of which are influenced by the intensity and duration of an activity (Enoka, 1995). The demands placed on individuals during aerobic exercise of a continuous nature have been the focus of many investigations; while in contrast, demands from exercise of an intermittent nature have been relatively understudied (Reilly, 1997; Noakes and Durandt, 2000; Christie *et al*., 2008). Exceptions include studies on the mode, duration and frequency of player activities in hockey, rugby, soccer and Australian football, which have been the focus of many investigations leading to enhanced match performance through the identification of physiological adaptations (Stretch *et al*., 2000 and Duffield and Drinkwater, 2008).

Intermittent activities are characterised by alternations between periods of high and low intensity exertions, thus highlighting the complex nature of, and the difficulty in, assessing the demands induced by this form of exercise (Ferrauti *et al*., 2001). The repeated eccentric muscle actions brought about through the acceleration and deceleration activities observed during repeated sprints has been associated with performance decrements and hamstring injuries (Gabbe *et al*., 2006 and Highton *et al*., 2009). Injury surveillance data has supported this finding, identifying hamstring strains as the most common lower limb injury associated with intermittent sports (Gabbe *et al*., 2006). However, the research surrounding the specific form of muscle fatigue induced by repeated eccentric demands on the lower limb musculature has been rather limited.

CRICKET

INTRODUCTION

Cricket was first established towards the end of the sixteenth century as an outdoor sport, played mainly in the summer months, with the compilation of official laws in 1744 (Finch *et al*., 1999 and Woolmer and Noakes, 2008). It has evolved over the years from a more conservative, traditional match, to that of a highly competitive and professional nature, requiring high skill levels and peak training status of the players (Nunes and Coetzee, 2007). It has been described as a non-contact, whole body activity, characterised by short bouts of high-intensity exercise, interspersed with longer periods of much lower intensities (Finch *et al*., 1999; Noakes and Durandt, 2000; Ferrauti *et al*., 2001; Christie *et al*., 2008). Although the principles of the match remain constant throughout the many forms of cricket, both the duration and intensity of the match is known to vary. The different forms of the sport include the traditional test matches (five-day), one-day (50 over matches) and more recently, the limited overs matches (twenty20 or T20).

Test matches are characterised by four to five days of six hours of play each day, broken down into three intervals of two hours, separated by lunch and tea breaks as well as shorter drinks breaks. One-day matches are characterised by two three and a half hour sessions, interrupted by either a lunch or supper interval, and a maximum of two drinks breaks per session. Twenty20 matches consist of 20 overs lasting a total of three and a half hours, with each innings lasting 75 minutes. The only interruption in this form of the match is one drinks break per session. Cricket can be classified in terms of duration, as an increase in duration is characterised by a relatively low intensity of play, with the opposite inferred with regards to matches of a shorter duration (Fletcher, 1955 and Noakes and Durandt, 2000).

Although cricket matches are known to be of a longer duration than the high-intensity activities of soccer, hockey or rugby matches, the nature of the match is different, resulting in possible underestimations of the musculoskeletal and physiological demands placed on the players (Duffield and Drinkwater, 2008). Furthermore, the intermittent and unpredictable nature of cricket results in considerable variation in the physiological measures obtained (Ferrauti *et al*., 2001 and Petersen *et al*., 2010). Most high-intensity activities in cricket are of a relatively short duration, and not of maximal effort, thus cardiovascular demands of all players, with the exception of fast bowlers, have been thought to be relatively low (Noakes and Durandt, 2000).

Unlike many other sporting codes, such as rugby and soccer, there has been a lack of scientific research on both the sport itself as well as the players (Noakes and Durandt, 2000; Bartlett, 2003; Duffield and Drinkwater, 2008). Bowling has been more thoroughly investigated, with specific focus on the demands placed on the individuals and associated injury risk (Noakes and Durandt, 2000 and Bartlett, 2003). The lack of research on the remaining aspects of the match is surprising, as an understanding of the physical demands imposed on individuals during match-play is necessary in order to enhance training, reduce injury risk and thus improve performance (Duffield and Drinkwater, 2008). Furthermore, an increase in pace, risk, and expectations on batsmen have been observed as the match has developed. Thus, it is surprising that research into both the musculoskeletal and physiological demands on the players have been neglected (Finch *et al*., 1999). Batting in particular has been under-researched.

CHARACTERISTICS AND DEMANDS OF EACH POSITION

Cricket is considered a team sport of eleven individuals, however not all players are required to be on the pitch at one time. Each player possesses specific skills in the bowling, fielding or batting domain of the sport, thus contributing to the overall versatility and effectiveness of the team. The biomechanical, physiological and perceptual demands placed on the individuals in each domain are considerably variable, therefore highlighting the necessity to understand these demands.

Bowlers

Bowling requires the repetitive rotation, twisting and extension of the trunk in a short time period, while soft tissues of the body absorb ground reaction forces produced by the running activity (Finch *et al*., 1999 and Portus *et al*., 2000). Interestingly, those individuals with a greater stature, bone and muscle mass, and a lower relative fat mass generally have a more efficient bowling motion (Stretch *et al*., 2000). There are three known stages comprising the bowling action; the run-up to back foot impact, the delivery stride, and the release and follow through, all of which influence the technique of the bowler (Finch *et al*., 1999). The technique of the bowler is known to largely influence the likelihood of injury, with a side- or front-on technique associated with a reduced incidence of injury, and the combination of the two, or a mixed bowling technique associated with a greater incidence of injury (Finch *et al*., 1999). Bowling is known to be the more frequent focus of studies, with particular emphasis on injury prevention and the physiological demands placed on the relevant individuals (Finch *et al*., 1999; Noakes and Durandt, 2000; Bartlett, 2003; Duffield *et al*., 2009; Petersen *et al*., 2010).

Fielders

Fielders are known to include a combination of bowlers and batsmen, with few players solely specialising in fielding, thus studies focusing on fielding are relatively few (Finch *et al*., 1999 and Bartlett, 2003). Fielders require a set of skills revolving around stopping, retrieving and throwing the ball. In addition, the focus and concentration of these players must be maintained for durations longer than two hours (Bartlett, 2003). It has been suggested that one-day matches have resulted in fielding improvements when compared to the longer duration test matches; this is due to improved training status and improved techniques adopted during the match (Bartlett, 2003).

Batsmen

Batting in cricket is known to be a dynamic interceptive action, one of the more complex within-ball matches, and requires optimum coordination and control of these actions to ensure success (Stretch *et al*., 2000). Three task constraints need to be fulfilled to improve performance; identification of a moving object in the environment, making contact with the required velocity, and contact with the intended spatial orientation, to ensure accuracy (Savelsbergh and Bootsma, 1994). Complications may arise from the swerve, swing or drag of the ball, highlighting the necessity of the batsman to maintain optimal concentration (Stretch *et al*., 2000). The skills required for batting fall into three categories; visual and neurological skills, physical and biomechanical skills and psychological skills (Stretch *et al*., 2000 and Woolmer and Noakes, 2008). These skills ensure efficient information processing, decision-making, mental toughness, and physical conditioning, resulting in improved performance of the batsman (Woolmer and Noakes, 2008). In contrast to bowlers, batsmen are commonly represented by individuals with a shorter, slighter build, smaller muscle and bone mass, as well as a greater relative fat mass (Stretch *et al*., 2000).

Variable physiological demands have been associated with batsmen depending on the type of match being played; high scoring rates are associated with one-day matches for example, and the opposite has been observed during five-day test matches (Stretch *et al*., 2000 and Christie *et al*., 2008). Although the cardiovascular demand on players may be relatively low during one-day matches, the activity may induce a higher load on other systems such as the skeletal muscles, presenting as fatigue, which if present may affect the performance levels of the players (Noakes and Durandt, 2000). Successful one-day cricket batsmen must be able to increase running velocity at a rapid rate in order to achieve maximum speed or greater acceleration, this ability would be affected should muscle fatigue be present (Cronin and Hansen, 2005 and Nunes and Coetzee, 2007).

FATIGUE

Fatigue is a complex multifactorial phenomenon, resulting in a reduction in both physiological and psychological performance parameters (Enoka, 1995). It is a continuous process, transforming the functional state of the system until termination of exercise (Balasubramanian and Jayaraman, 2009). Muscle fatigue in particular can be defined as a time-dependent reduction in both the force generating capacity and power output of a muscle induced by an activity (Vøllestad, 1997; Gandevia, 1998; Kent-Braun, 1999; Girard *et al*., 2008; Taylor and Gandevia, 2008; Balasubramanian and Jayaraman, 2009; Skurvydas *et al*., 2010). It is well supported that fatiguing muscles result in performance decrements; this is due to a reduction in muscle power and endurance as well as motor skill performance (Enoka, 1995; Vøllestad, 1997; Girard *et al*., 2008). It has further been suggested that impairments in performance may be due to several factors including the type of muscle action, exercise intensity and duration, motor unit behaviour, the muscle group as well as motivation (Enoka, 1995 and Girard *et al*., 2008). Recovery periods are an important aspect in limiting the occurrence of fatigue during high-intensity intermittent exercise (Girard *et al*., 2008). Little research has focused on the possible mechanisms responsible for changes in neuromuscular function induced by intermittent exercise, as well as the changes observed in the neuromuscular system following the progression of exercise of an intermittent nature (Girard *et al*., 2008).

It has been proposed that the muscle fatigue experienced during cricket activity could be due to repeated eccentric muscle damage resulting from repeated deceleration activities, common to all types of play including bowling, batting and fielding (Thompson *et al*., 1999; Noakes and Durandt, 2000; Bartlett, 2003; Gabbe *et al*., 2006; Pull and Ranson, 2007; Highton *et al*., 2009). Muscle fatigue progresses from the onset of exercise and recovery begins when exercise is terminated (Taylor and Gandevia, 2008). It has further been suggested that eccentric muscle actions induce a specific form of muscle fatigue represented by microscopic muscle damage and thus sufficient recovery time is required to obtain normal muscle function and counteract the symptoms associated with this type of fatigue (Highton *et al*., 2009). A major consequence following eccentrically-based exercise is the reduction in muscular power and strength; this has a long-lasting effect and can be observed through force generating capabilities during isokinetic activities (Highton *et al*., 2009). The degree of strength and power decrements observed following eccentric muscle actions is dependent on the intensity of the muscular activity (Taylor and Gandevia, 2008). If the activity is submaximal in nature, then muscular fatigue may occur without the associated decrement in performance, this being due to the recruitment of additional muscles in order to compensate for those that are fatiguing (Taylor and Gandevia, 2008).

Fatigue has been found to originate in several sites that can be divided into two main categories; central or peripheral fatigue depending, to some degree, on the task characteristics (Enoka, 1995 and Girard *et al*., 2008). There is however a lack of clarity regarding the relative roles of both the central and peripheral factors in muscle fatigue development (Kent-Braun, 1999). Fatigue may be referred to as a safety mechanism, controlled either by central or peripheral components, preventing injury development or metabolic crisis (Balasubramanian and Jayaraman, 2009). It has been suggested that both central and peripheral fatigue develop at a slower rate during exercise of a submaximal nature (Taylor and Gandevia, 2008). Peripheral fatigue has been found to occur during many different forms of exercise, while an increasing volume of evidence suggests central fatigue to be more common (Skurvydas *et al*., 2010). Characteristics of both forms of fatigue are a failure of the contractile capacity of the involved muscles, with a reduced tolerance to muscle stretch and a delayed transfer from muscle stretch to muscle shortening during the stretch-shortening cycle (Noakes, 2000). This delay in transfer results in increased durations of the phases of deceleration and acceleration in running.

PERIPHERAL FATIGUE

Peripheral fatigue is known to be located distal to the neuromuscular junction, and results in the reduction in force and power production (Gandevia, 1998; Girard *et al*., 2008; Taylor and Gandevia, 2008). More specifically, a reduction in the contractility of muscle fibres is observed, due to specific metabolic events within the active muscle (Kayser, 2003). The factors primarily involved in peripheral fatigue include excitation-contraction coupling failure and metabolic inhibition of the contractile process (Kent-Braun, 1999). Failure in the excitation-contraction coupling, which is associated with a slow time course of recovery, results from prolonged periods of low-intensity exercise (Kent-Braun, 1999). However, during high-intensity exercise, the accumulation of intramuscular metabolites as well as the slowing of muscle relaxation has been associated with fatigue development (Gandevia, 1998 and Kent-Braun, 1999).

CENTRAL FATIGUE

Central fatigue refers to the physiological processes occurring within the central nervous system resulting in muscle fatigue, and is found to occur in sites proximal to the neuromuscular junction (Enoka, 1995; Girard *et al*., 2008; Taylor and Gandevia, 2008). The central nervous system receives feedback from various sources involved in exercise, and limits the intensity and duration of skeletal muscle recruitment in order to maintain the integrity of the individual (Kayser, 2003). This form of fatigue can be defined as the progressive failure of voluntary muscle activation, associated with the slowing of motor unit firing rates, induced by a form of activity (Taylor and Gandevia, 2008). It has been suggested that the central components of fatigue have a dramatic influence on the reduction of muscle force during intermittent exercise (Kayser, 2003 and Girard *et al*., 2008). An alteration in neurotransmitter function within the brain associated with three aspects; a reduction in the excitatory input, an increase in the inhibitory input and reduced responsiveness of motor neurons due to a change in the associated intrinsic properties, may reduce the ability to recruit the optimal number of motor units within the active muscle resulting in fatigue (Girard *et al*., 2008 and Taylor and Gandevia, 2008). In order to maintain fatiguing contractions, a central command signal activating the muscles involved in the task must be sustained by the motor cortex (Enoka, 1995). Motivation plays an important role in the development of a force; inadequate motivation results in an insufficient force production during a fatiguing contraction (Enoka, 1995). The central nervous system has the ability to distribute activity at the motor-unit and neuromuscularcompartment levels, thus influencing force production and possible fatigue of the muscle group involved (Enoka, 1995).

Central Governor

Although still debated, it has been widely accepted that a ‘governor’ exists as a method of limiting activities that may result in whole-body damage (Noakes 2000). There has been much controversy over the identification of the ‘governor’. Although glycogen stores, cardiac output, or maximum oxygen uptake have all been considered, the most widely accepted theory is that the central nervous system governs the limit to exercise (Kayser, 2003). This ‘governor’ would inhibit the recruitment of skeletal muscle beyond an exercise intensity and duration where the heart or other vital organs could potentially be at risk (Kayser, 2003).

PHYSIOLOGICAL MODELS OF FATIGUE

It is well supported that the limitations to exercise can only be determined when models incorporating known physiological factors limiting performance, are used (Noakes and Durandt, 2000 and Noakes 2000) It has been suggested by Noakes and Durandt (2000) that none of the proposed models used to determine the nature of exercise-induced fatigue are able to adequately explain the fatigue experienced during cricket. The current models include five possibilities; the Cardiovascular-Anaerobic model, the Energy Supply-Energy Depletion model, the Muscle Power-Muscle Recruitment model, the Biomechanical model and the Psychological model (Noakes, 2000 and Noakes and Durandt, 2000). Of the models mentioned, both the Muscle Power-Muscle Recruitment and the Biomechanical model are of particular relevance to cricket.

Muscle Power-Muscle Recruitment Model

This model proposes that the fatigue experienced may be due to the cerebral motor cortex progressively reducing the skeletal muscle recruitment (Noakes and Durandt, 2000). This fatigue corresponds with central fatigue, associated with a reduction in cerebral motor cortex activity (Enoka, 1995). The resultant termination of exercise is therefore due to the reduction in motor cortex activity leading to a reduced recruitment of skeletal muscle, and not due to peripheral skeletal muscle fatigue (Noakes and Durandt, 2000). The cerebral cortex thus acts as a 'governor' to alter skeletal muscle recruitment, thereby preventing an increase in muscle activity levels represented by electromyography (EMG) which could otherwise lead to whole-body damage (Noakes and Durandt, 2000).

Biomechanical Model

This model proposes an alteration in skeletal muscle function and a loss of elastic energy production following repetitive eccentric muscle contractions (Noakes and Durandt, 2000). These repetitive contractions are most pronounced in shuttle running, which accurately reflects the acceleration and deceleration required for turning during running activities (Noakes and Durandt, 2000). This model is of particular relevance to the muscle fatigue observed during batting in cricket. Batting requires high levels of eccentric muscle actions during the repeated rapid acceleration and deceleration observed when running between the wickets (Faulkner, 2003 and Gabbe *et al*., 2006). Sufficient time is required in order to fully recover from muscle damage induced from this form of activity (Noakes and Durandt, 2000). It has been suggested that an increase in muscle strength may reduce the damage associated with repeated eccentric muscle actions (Noakes and Durandt, 2000).

ECCENTRIC MUSCLE ACTIVITY

Eccentric muscle actions refer to the simultaneous contraction and lengthening of a muscle; this has been observed to occur when the contracting muscles exert a braking force during deceleration activities (Enoka, 1996; Whitehead *et al*., 1998; Brockett *et al*., 2001; Faulkner, 2003; Gabbe *et al*., 2006). This muscle action results in the active lengthening of the involved skeletal muscle, with a simultaneous force resistance (Kendall and Eston, 2002 and Nosaka *et al*., 2002). As batsmen are required to run repeatedly between the wickets in order to increase the run total, eccentric muscle activity is a common occurrence when participating in the sport. It is widely supported that eccentric muscle actions result in greater force production and require less work than concentric muscle actions (Anderson *et al*., 1991; Kellis and Baltzopoulos, 1995; Faulkner, 2003). Furthermore, in order to obtain the required level of force generation, these lengthening muscle actions require a lower level of voluntary activation by the nervous system (Armstrong, 1984; Armstrong, 1990; Eston *et al*., 1996; McHugh *et al*., 2000).

Movement involved in activities is rarely isolated to lengthening muscle actions, but rather the combination of eccentric and concentric muscle actions forming the stretch-shortening cycle, which is observed during functional activities (Enoka, 1996). This cycle is typical of many athletic activities, and involves the eccentric loading of the muscle immediately followed by a concentric muscle action (Anderson *et al*., 1991; Enoka, 1996; Rassier *et al*., 1999; Byrne *et al*., 2004). The stretch-shortening cycle has the ability to enhance the work done by the involved muscles by improving mechanical efficiency, attenuating impact forces, and maximizing performance (Enoka, 1996). Four mechanisms underlying performance enhancement during the stretch-shortening cycle have been identified; the time available for force development, the storage and reutilisation of elastic energy, the restored potential of contractile machinery, as well as the contribution of reflexes (Byrne *et al*., 2004).

As eccentric muscle actions form part of the stretch-shortening cycle, exercise-induced muscle damage is a common occurrence following exercise of this nature (Anderson *et al*., 1991 and Byrne *et al*., 2004). Repeated eccentric contractions have a greater likelihood in resulting in muscle damage due to impaired muscle structure, function and metabolism (Enoka, 1996; Brockett *et al*., 2001; Byrne and Eston, 2002; Jaskólski *et al*., 2007; Highton *et al*., 2009; Skurvydas *et al*., 2010). The exercise-induced muscle damage resulting from lengthening muscle actions is characterised by the following symptoms; soreness, stiffness and swelling of the involved muscles (Cleak and Eston, 1992; MacIntyre *et al*., 1995; Enoka; 1996; Connolly *et al*., 2003;

Jaskólski *et al*., 2007). This impaired function has been observed to last for long durations, whereas muscular strength decrements have been observed immediately following eccentric exercise, followed by a linear recovery over a seven day period (Byrne and Eston, 2002 and Highton *et al*., 2009). It has also been suggested that damage to a particular muscle from eccentric exercise may predispose the muscle to injury, and have a high rate of recurrence (Friden *et al*., 1981; Friden *et al*., 1983; Gabbe *et al*., 2006).

Eccentric muscle actions differ from concentric muscle actions, as the actomyosin bonds do not rely on an ATP-dependent process to detach, but rather follow a mechanical method (Flitney and Hirst, 1978 and Enoka, 1996). This loading profile results in high stresses and strains placed on the involved skeletal structures, adding to the associated tissue damage (Enoka, 1996). The efficiency of eccentric muscle actions results in the high degree of muscle strain distributed over fewer muscle fibres (Enoka, 1996 and McHugh *et al*., 2000). Although eccentric muscle actions are associated with greater force-producing capabilities, the involved muscles require a reduced level of voluntary activation by the nervous system, suggesting unique activation strategies are associated with this form of muscle action (Kellis and Baltzopoulos, 1995; Enoka 1996; Faulkner, 2003). During eccentric muscle actions, the sarcomeres are stretched beyond the myofilament overlap and on relaxation become disrupted (Brockett *et al*., 2001). These disruptions enlarge due to the repeated muscle actions and result in micro-tears and a loss of calcium homeostasis (Armstrong, 1990 and Brockett *et al*., 2001). Additional factors are altered during eccentric muscle actions and result in sarcolemmal disruption, dilation of the transverse tubule system, deformation of the myofibrillar components, division of the sarcoplasmic reticulum, tears within the plasma membrane, swollen mitochondria, cytoskeletal damage, and changes in the extracellular myofiber matrix (Enoka, 1996). Delayed-onset muscle soreness (DOMS) is associated with these abnormalities, with an increase in the pain experienced peaking at 24 to 48 hours following exercise with complete recovery within 5 to 7 days (Enoka, 1996).

Structural adaptations have been observed in muscles following exercise, particularly those which involve eccentric muscle actions; these adaptations occur due to the activated inflammatory response and the modified neural command controlling the movement (Enoka, 1996). As batsmen are required to accelerate and decelerate repeatedly during a one-day match, eccentric muscle actions occur at a relatively high frequency, highlighting the high eccentric load placed on the musculoskeletal system of the players.

FUNCTIONAL CONSEQUENCES OF ECCENTRIC MUSCLE ACTIVITY

Force Loss

Exercise-induced muscle damage is frequently observed to occur following a bout of eccentric muscle activity (Byrne and Eston, 2002 and Clarkson and Hubal, 2002). A reduction in force production has been observed as the most reliable indirect indicator of exercise-induced muscle damage, and is associated with a force decrement for up to 24 hours following an eccentric exercise bout; this loss is for a considerably greater duration than that induced by a concentric exercise bout (Clarkson and Hubal, 2002; Jaskólski *et al*., 2007; Highton *et al*., 2009; Skurvydas *et al*., 2010). High-force eccentric exercise, involving maximal or near maximal eccentric muscle actions, has been associated with greater strength losses and recovery periods (Clarkson and Hubal, 2002). Following bouts of eccentric muscle actions, fast-twitch muscle fibres have been identified as being more susceptible to damage than slow-twitch muscle fibres; this damage presents as a reduction in force-producing capabilities (Jaskólski *et al*., 2007). Following maximal eccentric activities several aspects have been identified; firstly, a 35% reduction in maximum knee extensor strength, immediate neural activity increases which persisted for two days following the controlled activity, as well as a reduction in the rate of force development in the involved muscles (Komi and Viitasalo, 1977). More recently, reductions in force have been identified in knee extensor strength following an eccentric exercise protocol involving the quadriceps musculature; initial decrements in muscle strength of up to 40%, with long lasting decrements up to seven days following the exercise bout (Byrne and Eston, 2002).

These reductions in strength have functional implications in sporting activities, as athletes may have a decreased ability to perform at the required rate, resulting in performance decrements and an elevated injury risk. A dose-response relationship is therefore suggested, as an increase in eccentric load has been associated with greater reductions in muscle strength (Clarkson and Hubal, 2002).

Length-Tension Relationship

Hamstring musculature reach optimal lengths at the more extended knee joint angles, alternatively smaller knee joint angles represent that of optimal length in the quadriceps musculature (Aagaard *et al*., 1998 and Tourny-Chollet and Leroy, 2002). As such, a reduced force development may be observed in the quadriceps muscles under optimal knee angles. Following a bout of eccentric activity, a shift in the angle for optimal torque production has been identified, indicating that longer muscle lengths are associated with maximal force production (Enoka, 1996; Whitehead *et al*., 1998; Rassier *et al*., 1999; Byrne and Eston, 2002; Clarkson and Hubal, 2002). During eccentric muscle actions a greater tension is observed in the involved muscles, this tension being less affected by changes in velocity than concentric muscle actions (Westing *et al*., 1991 and Komi *et al*., 2000).

Similarly to force decrements, the shift in the length-tension relationship towards the optimum has been identified as a reliable measure of exercise-induced muscle damage, independent of fatigue, with the degree of the shift correlating to the extent of the muscle damage (Jones *et al*., 1997 and Morgan *et al*., 2004). Additional factors influencing the degree of the shift include the length of the involved muscle during eccentric activity, as well as the volume and intensity of the eccentric work bout (Whitehead *et al.,* 2001). This increase in volume and intensity is associated with a concomitant increase in the magnitude of the shift.

Dynamic joint stability can be ensured by the hamstring muscles during forceful knee extensions at high velocities (Aagaard *et al*., 1998 and Tourny-Chollet and Leroy, 2002). It has been suggested by Bennell *et al*. (1998) that this dynamic form of knee stability is an important aspect in activities involving running and rapid turning. The presence of an inhibitory mechanism is supported by the reduction in neural control to agonist muscles under conditions of high muscle tension, thereby reducing the risk of injury (Westing *et al*., 1991).

Force-Velocity Relationship

The force-velocity relationship, taking both the speed and level of activation from the voluntary command into account, has been identified as a method of identifying the force a muscle can exert (Enoka, 1996). A concentric muscle action shortening at a fast rate results in a reduced force production. Alternatively, an eccentric muscle action is largely unaffected by the various speed of muscle lengthening, thus the functional hamstring:quadriceps (H:Q) ratio increases (Enoka, 1996; Aagaard *et al*., 1998; Tourny-Chollet and Leroy, 2002). Although it has been identified that eccentric muscle actions have the ability for greater force production, this is associated with lower voluntary activation by the nervous system (Enoka, 1996).

Maximal concentric force has been observed to decrease with an increase in the velocity of the muscle contraction whereas, independent of contraction velocities, forces greater than produced concentrically were identified during maximal eccentric muscle contractions (Aagaard *et al*., 1998).

Neuromuscular Control

It was previously believed that the neural control for isometric, concentric and eccentric muscle actions were similar, with the nervous system identifying the amount of muscle activation required (Enoka, 1996). Eccentric muscle actions would therefore occur when the muscle torque was less than the torque corresponding to the load. More recent discoveries regarding the types of muscle actions and the differences between each, during both maximal and submaximal muscle actions, have identified alterations in the rate of discharge, the order of recruitment, and the force at which motor units are recruited (recruitment threshold) (Enoka, 1996).

Eccentric muscle actions involve lower rates at which the motor neurons are discharged, with only a few action potentials discharged at one time (Nardone *et al*., 1989 and Howell *et al*., 1995). The statement that neural commands for eccentric muscle actions are unique is supported by the alteration in recruitment order of the motor units (Enoka, 1996). Furthermore, the recruitment threshold for both concentric and eccentric muscle actions displayed lower values when compared to that of isometric muscle actions, indicating the change in recruitment threshold is mediated by the brain (Enoka, 1996).

Repetitive eccentric exercise is associated with repetitive stretch shortening cycles and results in prolonged reductions in numerous factors, more specifically, EMG activity of the involved muscles, maximal force production, regulation of muscle and joint stiffness, ground reaction forces, the sensitivity of the stretch reflex and vertical jump performance (Nicol *et al*., 1991a; Nicol *et al*., 1991b; Avela *et al*., 1999).

A change in neuromuscular function was identified by a reduction in the following; maximal integrated EMG (iEMG) of two muscles in the quadriceps, maximal torque produced during isometric knee extensions and drop jump performance (Nicol *et al*., 1991a and b). Byrne and Eston (2002) identified further decrements in vertical jump performance for up to four days following exercise-induced muscle damage. Eccentric exercise in particular has also been shown to result in the reduction in the force to iEMG ratio of the knee extensors, indicating a decrement in the neuromuscular efficiency of the muscles involved (Komi and Viitasalo, 1977 and Byrne *et al*., 2004).

Hamstring:Quadriceps Strength Ratio

The maximal hamstring muscle strength relative to the maximal quadriceps muscle strength (H:Q), obtained through isokinetic dynamometry, enables a quantitative measure of torque from agonist and antagonist muscle actions surrounding the knee joint (Aagaard *et al*., 1998 and Rosene *et al*., 2001). It is utilised in order to determine similarities between the hamstring and quadriceps musculature, moment-velocity patterns, to assess knee functional ability and to highlight any muscle imbalances that may predispose muscles to injury (Cometti *et al*., 2001 and Rosene *et al*., 2001).

This ratio has traditionally been expressed as concentric hamstrings to quadriceps strength. However, it has more recently been expressed as eccentric hamstrings to concentric quadriceps strength (extension) and concentric hamstrings to eccentric quadriceps (flexion) to express a more functional ratio of the agonist to antagonist strength ratio (Aagaard *et al*., 1998; Rosene *et al*., 2001; Coombs and Garbutt, 2002; Tourny-Chollet and Leroy, 2002). The $H_{(ecc)}$:$Q_{(con)}$ functional ratio provides an indication of the deceleration function of the hamstrings during a maximal strength extension activity by the quadriceps muscles (Tourny-Chollet and Leroy, 2002). The ratio is position- and velocity-dependent, and provides an essential indicator for the predisposition to injury (Rosene *et al*., 2001). It has been suggested that the functional H:Q ratio highlights the contractile force-velocity and force-length properties of the agonist-antagonist muscles about the knee joint (Aagaard *et al*., 1998). During isokinetic knee extension and flexion, co-activation of the hamstring and quadriceps musculature has been identified at varying degrees and velocities up to $400°.s^{-1}$ (Coombs and Garbutt, 2002). An individual may be predisposed to injury due to well-developed quadriceps musculature reducing antagonist co-activation in the hamstrings during extension loads, resulting in the surrounding ligamentous structures supporting the majority of the imposed load (Rosene *et al*., 2001).

The normal H:Q ratio through the full range of motion during knee extensions, has been accepted to fall between 50 to 60% for very slow speeds, 60 to 70% for medium speeds, and 70 to 80% for speeds greater than 180°.s^{-1} (Bennell *et al*., 1998 and Rosene *et al*., 2001). An increase of the ratio towards 100% indicates an increased functional capacity of the hamstrings to stabilise the knee during active knee extension (Aagaard *et al*., 1998; Rosene *et al*., 2001; Coombs and Garbutt, 2002). Although it has been suggested that a lower H:Q ratio is associated with a higher predisposition to injury, relationships resulting in this have not been widely demonstrated (Aagaard *et al*., 1998; Bennell *et al*., 1998; Coombs and Garbutt, 2002).

An increase in eccentric hamstring strength would therefore result in greater stability of the knee joint (Aagaard *et al*., 1996). Knee flexor strength is important in order to ensure joint stabilization, particularly during eccentric muscle actions, therefore highlighting the importance of strength training (Cometti *et al*., 2001). The functional H:Q ratio was further identified as a useful tool to provide information on knee stability and injury risk, used specifically during sporting activities.

INJURIES IN CRICKET

Injury profiles differ between social and elite cricket, with an increase in injury prevalence at an elite level due to the increase in workload and match intensity (Orchard *et al*., 2010). Injury incidence per 10 000 player hours within both the Twenty20 and one-day match formats have been identified as greater than that during multiple day matches (Orchard *et al*., 2010). Of the players, fast bowlers in particular have been identified at greatest risk for injury during pre-season matches, and those towards the end of the season than either batsmen or fielders (Finch *et al*., 1999; Stretch, 2001; Orchard *et al*., 2002; Stretch, 2003; Stretch, 2007; Mansingh *et al*., 2010). The body regions most frequently affected in bowlers include the trunk/lumbar spine and the groin or thigh area (Stretch, 2001 and Orchard *et al*., 2002).

Batsmen however have been identified as being at risk during matches characterised by a higher intensity, typical of limited overs matches (Orchard *et al*., 2002; Kilian and Stretch, 2006; Petersen *et al*., 2010; Stretch and Raffan, 2011). Cricket matches characterised by limited overs, Twenty20 matches in particular, require a higher work rate than that of multi-day cricket (Houghton, 2010). Factors increasing injury risk of batsmen refer to the repeated high-intensity sprinting between the wickets, rapid and repeated turning, as well as batting for long durations, thereby increasing the risk of sustaining impact injuries (Stretch, 1993; Stretch, 2001; Stretch, 2003; Stretch and Venter, 2005; Stretch and Raffan, 2011).

A study by Orchard *et al*. (2010), investigated the seasonal injury incidence over eleven seasons of Australian cricketers. Of particular importance was the dramatic increase in hamstring muscle strains particularly in more recent years. This was suggested to be the most prevalent of the reported injuries, observed in all components of the match (Milsom *et al*., 2007 and Orchard *et al*., 2010). Similarly, lower limb injuries were identified as the most common injury within South African sub-elite and elite cricketers, varying in prevalence from 22.8% to 50% of players, and within batsmen most commonly included muscle strains, particularly of the hamstring, quadriceps or calf within the lower limb musculature, as well as impact injuries (Stretch, 2001).

Hamstring muscles have a biarticular muscle arrangement, indicating the muscle fibres are subjected to extensive length changes during activities (Brockett *et al*., 2001). Notably large lengths are obtained during decelerating activities, similar to those activities observed in cricket, indicating this as a high risk for hamstring strain injuries to occur (Brockett *et al*., 2001). Frequent bursts of running, and thus eccentric muscle activity, may further result in microscopic damage of the hamstring muscles, presenting as a strain or tear depending on the severity of the damage (Edgerton *et al*., 1996; Croisier *et al*., 2002; Clark, 2008; Greig and Siegler, 2009). Hamstring strains are known to have a high rate of recurrence, therefore increased efforts to prevent these forms of injuries are necessary (Bennell *et al*., 1998).

Fatigue may further augment the risk of hamstring injury as it results in impaired running technique, so placing an increased load on the hamstring muscles to act as the stabiliser (Clark, 2008). During running, a closed kinetic chain activity, hamstring musculature are activated in the last third of the swing phase. Their primary function during this movement is to decelerate knee extension, resulting in eccentric muscle activity, and oppose the quadriceps muscle actions (Bennell *et al*., 1998 and Tourny-Chollet and Leroy, 2002). At ground contact the hamstring muscles then switch from eccentric to concentric muscle actions, resulting in extreme force development, greater than that produced by any other muscles in the lower limb (Bennell *et al*., 1998). The extreme forces placed on the hamstring musculature, combined with strength imbalances between the hamstring and quadricep muscles may predispose individuals to hamstring strain injuries (Bennell *et al*., 1998).

It has been accepted that hamstring strains are multifactorial in nature, with factors such as muscle flexibility, neural tension and lumbar lordosis influencing the risk of injury (Bennell *et al*., 1998; Croisier *et al*., 2002; Clark, 2008). However, the more common risk factors predisposing the hamstring muscles to injury refer to reduced strength and/or endurance of the muscles of the hamstring, strength imbalances between the hamstring and quadriceps muscles, and strength inequality of the right and left hamstring muscles (Bennell *et al*., 1998; Croisier *et al*., 2002; Clark, 2008; Greig and Siegler, 2009).

Frequent, sudden explosive actions result in an increased risk of muscle strain, observed specifically during a propulsion or deceleration activity (Pull and Ranson, 2007 and Greig and Siegler, 2009). These muscle strain injuries vary in the level of severity from minimal loss of muscle function due to minor damage, to the more severe, represented by drastically impaired function, severe reductions in muscle strength as well as swelling and obvious bruising (Pull and Ranson, 2007). A decline in hamstring muscle strength, associated with fatigue, has been observed over time, this is due to the greater action of the hamstring muscle complex in controlling the running observed in an intermittent activity profile (Greig and Siegler, 2009). The hamstring musculature is responsible for slowing the momentum of the swinging leg in preparation for ground contact during the deceleration phase in a sprinting activity, thus leaving this muscle complex vulnerable to injury during this stage of the activity (Bennell *et al*., 1998; Tourny-Chollet and Leroy, 2002; Gabbe *et al*., 2006; Pull and Ranson, 2007).

CONCLUSION

The eccentric demands resulting from repeated sprinting between the wickets are evident in a cricket activity. An increase in the prevalence of musculoskeletal injuries, particularly muscle strains within the hamstring musculature of the lower limbs, has been associated with the repeated high-intensity accelerations and decelerations required during activities of an intermittent nature. Literature has supported the associated reduction in force production, as well as increased predisposition to injury due to the exercise-induced muscle damage induced by prolonged periods of eccentric exercise.

CHAPTER III

METHODS

PILOT TESTING

Prior to experimentation, extensive pilot studies were conducted to ensure the accuracy and reliability of the laboratory-specific protocol developed. The pilot studies involved specific analyses of the musculoskeletal, physiological and perceptual demands placed on batsmen during a simulated cricket work bout. The work bout highlighted the demands induced on the players during repeated-sprint activities. The results obtained from the pilot studies were then analysed and adjustments to the experimental conditions were made in order to best represent the demands placed on batsmen during one-day matches of both a high- and moderate-intensity (represented by the run rate). Further, these pilot investigations were conducted in order to familiarise the experimenter with the equipment utilised during the testing procedures and furthermore, to establish the efficacy of the demands placed on the players.

ETHICAL CONSIDERATIONS

INFORMED CONSENT

All players participating in the study were informed both verbally and in writing (Appendix A, pg 124), of the nature of the study. Those players recruited were required to sign a letter of informed consent (Appendix A, pg 128), stating that all aspects of the study were understood, all questions regarding the protocol answered, and that each player had the right to withdraw at any time due to the voluntary nature of the study. This process occurred without any pressure from the primary researcher, coaches or team members involved. Prior to the onset of player recruitment, ethical clearance was given by the Department of Human Kinetics and Ergonomics Ethics Committee (Appendix A, pg 123).

PRIVACY AND ANONYMITY OF RESULTS

In order to ensure anonymity of each participant, all players were coded so that none of the information obtained could be traced back to any of the participants. Players were also informed that the information recorded would be kept on file for statistical purposes, and only one copy would be held by the department for possible future publications.

PLAYER SELECTION

Several players that fell into the sub-elite or elite category within the Eastern Cape Province of South Africa were identified, and the relevant coaching staff contacted. The remaining players consisted of individuals involved with Eastern Province or Country District teams in and around the Grahamstown area, as well as players participating in the internal cricket league held by Rhodes University in Grahamstown. Players interested in participating in the investigation attended specific sessions during which information regarding the study was provided to the players and, following agreement to participate, informed consent was obtained from the participants. All players then completed a physical activity screening questionnaire, in order to obtain specific information regarding health status and injury history (Appendix A, pg 130). This questionnaire provided additional insight into the medical history of each player. This included past diseases, disorders or injuries, as well as highlighting any medication the player was currently taking, whether prescribed or self-medicated. It also provided insight as to whether the any of the players were smokers, and provided an exercise history for each individual.

PLAYER CHARACTERISTICS

Twenty male cricketers playing at University, sub-elite or elite levels were recruited through advertisements or through referral from relevant coaches. These players were between the 18-35 year age range, had no history of injury, were in the top 5 of the batting order and were healthy at the time of testing. Although the age range for player selection was 18-35 years, the mean age of participants was 22.6(±4.74) years.

EXPERIMENTAL DESIGN

Previous research within the sport has focused on the physiological demands of cricketers; this has ranged from predicted energy expenditure to more recently, oxygen consumption, heart rate and energy expenditure (Fletcher, 1955; Gore *et al*., 1993; King, 2002; Christie *et al*., 2008). This research revealed that cricket was more physically taxing than previously believed and highlighted the need for more research to be conducted within the field (Gore *et al*., 1993; King, 2002; Christie *et al*., 2008). A greater understanding of the number of repeated sprints (run total) and the opportunity for recovery between high-intensity efforts was obtained from time-motion analyses data in a study conducted by King (2002), and further analyses on more recent international one-day matches were conducted in 2010 by the primary researcher. These analyses allowed for the demands experienced during one-day matches to be accurately represented in a simulated laboratory protocol of seven overs.

Pilot investigations conducted within the department involved investigations into both the physiological demands placed on batsmen and the isokinetic muscle strength changes in the lower limb musculature of batsmen following a repeated sprint work bout (Christie *et al*., 2011a and b). The investigations revealed that the physiological demands were similar to those previously identified by Christie and colleagues (2008). An overall strength decrement of the quadriceps and hamstring musculature, both concentrically and eccentrically however indicated the necessity for further investigation using a larger sample (Christie *et al*., 2011a and 2011b). Isokinetic dynamometry enabled muscle strength decrements to be determined. Two velocities were selected for the players; one slower, at 60°.s^{-1} to determine muscular strength, and another faster at 240 - 300°.s^{-1} which is a speed that more closely represents those experienced during free exercise (Williams, 1994; Cometti *et al*., 2001; Nunes and Coetzee, 2007). This strength decrement is supported by literature stating that eccentric exercise involving repeated rapid acceleration and deceleration activities results in a particular form of muscle fatigue (Highton *et al*., 2009). This muscle fatigue is due to ultra-structural skeletal muscle damage resulting in strength, power and overall performance decrements (Byrne and Eston, 2002 and Highton *et al*., 2009), especially within the hamstring musculature. Although this reduction in isokinetic strength, coupled with recent injury statistics highlights the need for research focusing on repeated eccentric movements and the associated demands placed on the lower limb musculature, no recent investigations have focused on the demands associated with high- and moderate-intensity running between the wickets; therefore this topic remains unaddressed.

DEVELOPMENT OF WORK BOUT

Previous research within the laboratory in the department of Human Kinetics and Ergonomics, Rhodes University included pilot studies conducted by Christie and colleagues (2008) and Christie *et al*. (2011a and 2011b), all developed from a batting-specific protocol developed by King (2002). This protocol was developed through time-motion analyses conducted on high-scoring one-day Internationals (ODI's) between 1991 and 2001. A high-scoring match referred to those with a run total of 260 or more. As no additional time-motion analyses had been conducted following those by King (2002), it was suggested that more recent matches needed analysis to ensure a work bout was developed that more accurately represented present day matches. For this research, more recent high-scoring one-day internationals from the 2010/2011 seasons were analysed including South Africa, West Indies, Pakistan, India, New Zealand, Australia and England. Specific observations during the analyses included: the time between bowling deliveries, time between overs as well as the mean run rate per over. For each of these analyses, 60% of the full matches were observed, corresponding to a total of 30 overs. This was done in order to exclude the fielding restrictions represented by Power Plays, which are known to result in a greater number runs scored by boundary shots rather than by sprinting between the wickets. The overs included in the analyses were therefore those that were observed to impact the musculoskeletal and perceptual demands of the batsmen to a greater degree than when the fielding restrictions were introduced.

Table I: Comparison between mean data obtained from the previous study to the present analyses.

	King (2002)	2010 Studies
Time Between Deliveries (seconds)	30	32.67
Time Between Overs (seconds)	60	79.80
Run Rate per Over	-	5.99

The results obtained were found to be of an increased duration than that observed by King (2002) (Table I). An increase in both durations between deliveries to the batsmen as well as between each over was observed. More specifically, in more recent one-day international matches the mean duration between each ball delivered was found to be 32.67 seconds as opposed to the 30 seconds found in the 2002 analyses. A further increase in the duration between each over, allowing for the change in bowler was observed to be 79.80 seconds, as opposed to the 60 seconds previously found by King (2002).

EXPERIMENTAL CONDITIONS

In order to compare the musculoskeletal, physiological and perceptual demands placed on the batsmen during both the high-and moderate-intensity conditions the experimental procedures were required to be as similar as possible, only differing in the run rate (represented by shuttle sprints), as this represented the intensity of each condition.

Within the laboratory, two creases representing the cricket pitch were demarcated along a wooden walkway, with a distance of 17.68 meters between them (Figure 1, pg 39). The protocol used in this study was adapted from that of King (2002) where the players, dressed in full cricket kit, were required to face seven overs of six balls (42 balls). The data obtained from the time motion analyses was then adapted into the King (2002) protocol, and adjustments to the duration between deliveries and overs were changed to 32.67 seconds and 79.80 seconds respectively. In order to ensure consistency and thus accuracy, each ball was delivered by the same research assistant as throw downs. This protocol ensured the musculoskeletal, physiological and perceptual demands on the players were representative of those experienced during high-scoring one-day matches.

A) B)

Figure 1: Laboratory where the experimental conditions were conducted with A) the view from where players faced the bowler, batting into the net and B) the view as players turned around and returned to the start.

Each batsman was required to participate in two conditions (Table II, pg 40). Condition 1 was reflective of a high-intensity match, represented by a high-volume sprint work bout. Players were required to face seven overs of six balls, and following every ball, sprinted a double shuttle run, resulting in a total of 12 runs each over and 84 runs overall. Condition 2 was reflective of a moderate-intensity match, represented by a moderate-volume sprint work bout. For this condition, players once again faced seven overs of six balls, and following every second ball, players were required to sprint a double shuttle run, resulting in a total of 6 runs per over, a total of 42 runs overall. Specific musculoskeletal (muscle strength and muscle activity), physiological (heart rate), perceptual (rating of perceived exertion and body discomfort) and performance (timing of each double sprint) measures were recorded at specific stages throughout the protocol. The musculoskeletal measures were obtained prior to, and following, each condition and the physiological and perceptual measures were recorded throughout the protocol, on the completion of each over. In addition, a performance measure was put in place. This took the form of an LED system and a beam crossing the end of the batting crease. As players started the double shuttle sprint, the beam was broken and this resulted in the start of a timer, only once the beam was broken a second time, indicating the return of the player, did the timer stop and the value recorded.

Table II: Design Matrix of the study

	Over 1	Over 2	Over 3	Over 4	Over 5	Over 6	Over 7
CONDITION 1							
CONDITION 2							

The following refer to:

CONDITION 1 – High-volume experimental condition

CONDITION 2 – Moderate-volume experimental condition

EQUIPMENT AND MEASUREMENTS

ANTHROPOMETRIC AND MORPHOLOGICAL MEASURES

Body Mass (With and without full kit)

Body mass was measured to the nearest 0.01 kilogram (kg) using a calibrated Toledo® electronic scale (model 8142). Players were firstly required to wear minimal clothing and remove footwear as well as any objects within the pockets of the clothing. Secondly, players were required to wear all protective cricket kit (Gloves, thigh guard, arm and elbow guard and leg pads), as in a match scenario, as well as running shoes, body mass was then measured as in the first scenario.

Stature

Stature was measured to the nearest centimetre (cm) using a Harpenden stadiometer. The players were required to remove their shoes, stand in an upright position facing forward, with three points in contact with the back of the stadiometer, namely the head, gluteus maximus and calcaneous. Stature was measured from the floor to the vertex in the mid-sagittal plane.

Skinfold Measures

Skinfolds were measured using a Harpenden skinfold calliper (Holtain Ltd., Crymych United Kingdom). Seven sites, namely; chest, triceps, subscapular, suprailliac, abdominal, thigh and medial calf were recorded. All measures were taken on the right hand side of the body, with the skinfold caliper perpendicular to the skinfold, placed halfway between the crest and base of each anatomical site, 10mm from the experimenter’s thumb and finger. Three sets of readings were recorded, if these were not within the 3% error margin, additional measures were ensured. Body density (BD) was then calculated using the equation developed by Jackson and Pollock (1978) as follows:

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

This value was then converted to body fat percentage using the equation developed by Siri (1961):

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

PHYSICAL PARAMETERS

The dominant lower limb of all players was used in measurements for all the physical parameters, having been determined prior to the start of testing.

Muscle Activity

Muscle activation was assessed prior to, and on completion of both conditions using an electromyography (EMG) device, the Biometrics Ltd DataLOG W4X 8, Gwent, United Kingdom. This device has eight analogue channels and two digital channels allowing for the simultaneous collection of a variety of data. The lower limb musculature was of particular importance to the study, more specifically the quadriceps and hamstring muscle complexes. Four muscles were selected due to their proximity to the surface; these included the vastus medialis (VM) and vastus lateralis (VL) to determine quadriceps muscle activation, as well as biceps femoris (BF) and semitendinosus (ST) to determine hamstring activation. Four analogue channels were thus used to measure muscle activity, one for each of the selected muscles to be tested, and one digital channel, which connected to a neutral electrode placed on an uninvolved muscle. In order to minimise electrical impedance, the areas on the dominant limb where electrodes were to be placed were shaved and cleaned with alcohol swabs, and once dry, the electrodes were attached to the surface of the skin directly over the muscle belly and muscular activity was observed (Figure 2 and 3, pg 43 and 44). The correct anatomical position for electrode placement was determined by the primary researcher palpating each specific muscle, and the distance of electrode placement from a specific anatomical point was recorded, ie: the anatomical point for the quadriceps muscles referred to the uppermost point of the patella. All information regarding muscle activity was transferred to a laptop via infrared telemetry for storage and data analysis purposes.

In order to analyse the raw EMG a data reduction tool, Data Analysis Version 3.32, was used. Initially, the raw EMG signal was filtered in order to eliminate the hum. The amount of EMG activity was then identified as the area under the curve for EMG (µV) over time (seconds); this resulted in an integrated EMG (iEMG) root mean squared (RMS) measurement. The RMS of the post-protocol EMG data, separated into the four speeds (6, 12, 15 and 21 km.h^{-1}) which comprised the normalization protocol (Table III, pg 44), was referenced to the RMS of the pre-protocol EMG data, grouping all speeds. This was done individually for both the high- and moderate-volume conditions, allowing comparisons to be made.

Figure 2: Diagrammatic representation of electrode placement for the hamstring musculature, semitendinosus on the left, and biceps femoris on the right (Muscle Tester Mega ME6000P16, Mega Electronics Ltd, Finland).

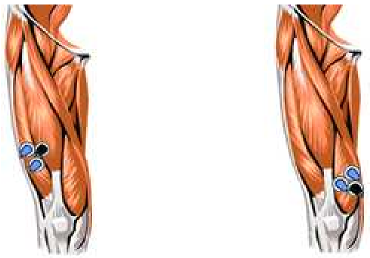


Figure 3: Diagrammatic representation of electrode placement for the quadriceps musculature, vastus lateralis on the left, and vastus medialis on the right (Muscle Tester Mega ME6000P16, Mega Electronics Ltd, Finland).

In order to determine muscle activation, a reference measure was obtained prior to testing from a three minute EMG protocol designed by Rahnama *et al*. (2006) (Table III, pg 44). This was then repeated following both experimental conditions, allowing for a comparison of the muscle activation patterns. The protocol developed by Rahnama *et al*. (2006) assessed lower limb muscular fatigue specific to an intermittent soccer activity which has been further utilised in Rugby Union studies (Brown and Christie, 2009).

Table III: The three minute EMG protocol designed by Rahnama *et al*. (2006).

Time (min:s)	**Speed (km.h^{-1})**	**Duration (min:s)**
00:00	6	01:10
01:10	5	00:20
01:30	12	00:15
01:45	5	00:20
02:05	15	00:15
02:20	5	00:20
02:40	21	00:15
02:55	5	00:20
03:00	Stop	

During the three minute protocol, players were required to walk, jog, stride and sprint on instruction, as the speeds altered (Table III). A speed of 5km.h^{-1} was the interface between the remaining speeds of 6, 12, 15 and 21 km.h^{-1}, thereby accurately representing an intermittent activity profile. This protocol was completed twice for each condition (pre- and post-protocol), and a treadmill was used in order for the speeds to be controlled manually. This data enabled information on the change in activation patterns of the quadriceps and hamstring muscles involved during the repeated sprinting between the wickets. It further resulted in conclusions to be drawn on the implications of varying intensities on player performance.

Muscle Strength

Muscle strength was assessed using isokinetic testing; this refers to the assessment of maximal muscle tension throughout a range of joint motion, set at a constant angular velocity (Perrin, 1993 and Franklin *et al*., 2000). Prior to each condition, baseline measures of isokinetic knee flexor/extensor concentric and eccentric strength were obtained using the Cybex 6000 Isokinetic Dynamometer. Changes in concentric and eccentric strength values were determined on completion of each condition. Standard knee flexion and extension protocols were used according to the manufacturer's instructions (CYBEX, Division of Lumex, Inc., Rononcoma, NY, 11779). The delivery of tests were randomized, and specific isokinetic speeds of 60°.s^{-1} and 270°.s^{-1} were selected in order to determine muscular strength (60°.s^{-1}), and a faster velocity that closely represents those experienced during free exercise (240 - 300°.s^{-1}) (Williams, 1994; Cometti *et al*., 2001; Nunes and Coetzee, 2007). Three repetitions were performed at each speed (60°.s^{-1} and 270°.s^{-1}), with a 30 second rest period between each set. The dynamometer was set up according to the anthropometric measures of each individual; these values were recorded for ease of set up for the testing session. Players were required to be habituated to the machine, and the movements required of them involved both the flexion and extension exercises under both concentric and eccentric settings. This ensured an increased accuracy in the measures obtained. Gravity was corrected for each individual, as a greater torque is known to occur when working with gravity when compared to working against gravity, thereby influencing the hamstring to quadricep (H:Q) ratio.

This would result in the prediction of a greater force produced by the hamstring musculature and a smaller force produced by the quadriceps musculature.

Both concentric and eccentric knee flexor and extensor strength was determined prior to, and following, each condition. The predetermined dominant lower limb of the player was involved in each testing session; once players were secured to the apparatus, they were required to perform a number of trials at each testing speed as part of the warm up. The testing protocols both included three repetitions at each speed, with a rest break in between. Players were instructed that each effort was required to be maximal in nature, throughout the entire range of motion. In order for this to be ensured, verbal encouragement was provided by the researcher throughout each protocol.

PHYSIOLOGICAL PARAMETERS

Heart Rate

All players were fitted with Polar Accurex Plus Heart Rate (HR) monitors and telemetry straps. The strap was placed around the torso of the player and aligned with the sternum, slightly below the pectoral muscles. The strap was tightened sufficiently in order for it not to slip, but not so that it was uncomfortable or constricting for the players. HR responses were recorded in beats per minute ($bt.min^{-1}$) during both the experimental conditions using a Polar Accurex Plus Heart Rate Monitor (Electro, Finland). Initial reference heart rates were obtained prior to testing; players were required to lie in a supine position for 2 to 5 minutes, where the lowest reading was recorded as the reference measure. Measures were then recorded following each over (6 balls faced) providing an indication of the physiological effort of each player.

PERCEPTUAL PARAMETERS

Rating of Perceived Exertion

Rating of perceived exertion (RPE) was used to determine the perceived physical effort by the players. Borg's rating scale (1970) (Appendix B, pg 138), ranging from a value of 6 representing 'minimal effort/strain' to a value of 20 representing 'maximal effort/strain', was used to identify perceived effort. Measures included both 'central' or cardiovascular effort, and 'local' or muscular strain, particularly of the lower limb musculature. The scale was explained to the participants, and players were familiarised with it and the specific feelings associated with each value on the scale. During the testing procedure, players were required to rate both 'central' and 'local' RPE following each over (after every 6 balls faced), during the period representative of a change in over.

Body Discomfort

Perceived discomfort of the whole body was measured using Corlett and Bishop's (1976) Body Discomfort Map (Appendix B, pg 140). This map includes an anterior and posterior view, divided into 28 regions; discomfort can then be identified on a scale of one to ten (minimal to maximal discomfort respectively). The map was explained in detail to each player in order to familiarise the individuals with accurate identification of perceived discomfort. Players were required to identify perceived body discomfort during the break following each over (following six balls).

ADDITIONAL EQUIPMENT

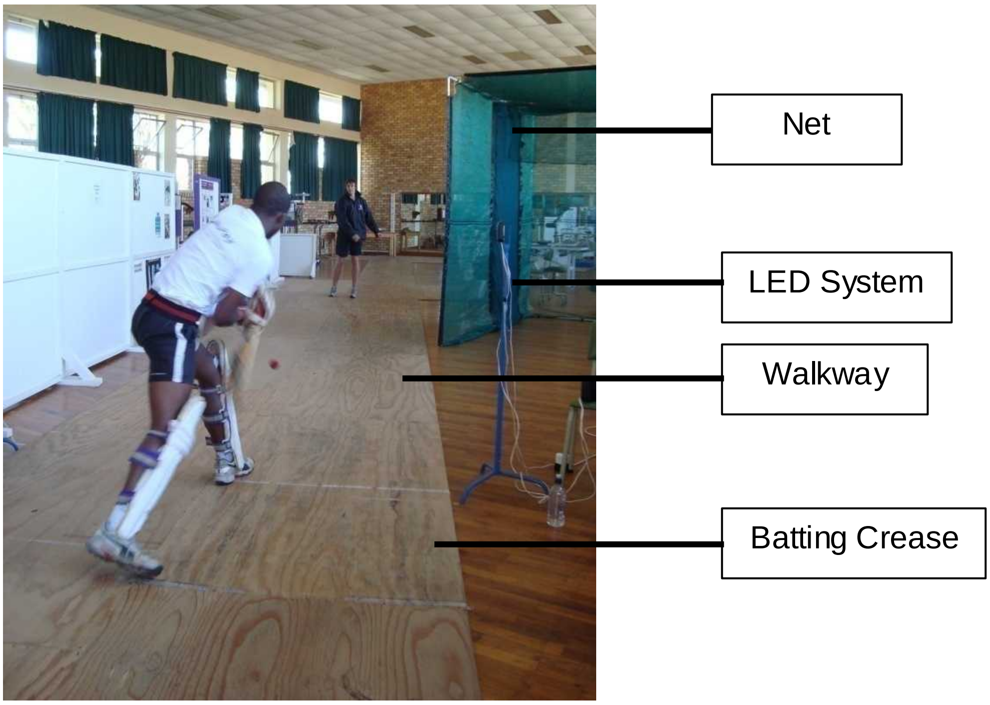


Figure 4: View of the laboratory highlighting the experimental set up, including all additional equipment.

Treadmill

A treadmill, specifically designed by the Department of Human Kinetics and Ergonomics, Rhodes University, was used during the 3 minute EMG protocol. As this protocol called for speeds varying from 5 km.h^{-1} to 21 km.h^{-1}, this treadmill was selected as it could reach the high speeds required. Everything was manually operated during the protocol, and immediately terminated if necessary.

Walkway

A wooden walkway, a distance of 17.68 meters in length, was constructed within a laboratory (Figure 1A, 1B and 4, pg 39 and 48). This walkway was comprised of an untreated plywood surface (120mm thick, 2440mm wide), resulting in an appropriate coefficient of friction. This, in combination with rubber-soled training shoes worn by each player, would provide adequate shoe/floor friction reducing the risk of slip, trip or fall accidents due to the surface.

LED System

In order to monitor the continuous performance of the players, a beam was set up between two LED systems, positioned at the batting crease (Figure 1A and 4, pg 39 and 48). Once the beam was broken, a timer started which only stopped when the beam was broken once again, indicating the player had returned to the crease. The sprint time for each double shuttle run was therefore recorded in order to ensure performance was maintained throughout each condition.

Net

A net (2m X 2m) was used during both testing conditions in order for the batsmen to block each shot and the ball to be directed into the net (Figure 5, pg 49). This ensured the safety of all individuals as well as all remaining equipment in the room, avoiding impact with the ball.

Figure 5: Net into which batsmen were required to bat.

EXPERIMENTAL PROCEDURES

In order to participate in the study, players were required to attend three sessions. The first involved an introduction to and explanation of the study and the remaining two sessions represented the two experimental conditions of a high- and moderate-volumesprint work bout. The experimental conditions were randomised in order to ensure that any differences observed could be directly attributed to the specific protocol, and not due to familiarisation and/or fatigue induced by the protocols. Both sessions II and III were required to be performed at the same time of day, within six to eight days of each other, in order for environmental conditions to be as similar as possible, and to minimise the influence of the fatigue induced by one condition on the other. All experimentation took place within the Department of Human Kinetics and Ergonomics (HKE) at Rhodes University, Grahamstown, South Africa.

SESSION I: INTRODUCTION AND BASELINE DATA COLLECTION

All participants were required to attend an introductory session within the HKE Department. This introductory session enabled the investigator to explain the details and objectives of the study to the players both verbally and in writing (Appendix A, pg 124), allowed each player to sign an informed consent (Appendix A, pg 128), as well as a physical activity screening questionnaire (Appendix A, pg 130) to ensure no risk would be imposed due to the exercise. In addition, the demographic, anthropometric and physiological data required for the investigation were collected, and adequate familiarisation with the equipment was ensured. The habituation to all equipment involved in the experimental procedures was extensive, however, particular importance was placed on treadmill running and the movements involved during isokinetic testing. The rating of perceived exertion (RPE) (Appendix B, pg 138) and body discomfort scale (Appendix B, pg 140) were adequately explained to the players and then players were habituated to using both scales. The specific baseline measures taken included: age, stature, two body mass measures (with and without full kit), skinfolds and reference heart rate. The fact that participation in the study was voluntary meant that players were permitted to withdraw at any time. Players were requested not to consume any alcohol or participate in any strenuous exercise 24 hours prior to the next testing session, not to consume any food three hours before testing, and to inform the researcher if the participant was not healthy. If the participant exhibited cold or flu symptoms or showed any other signs of ill health the researcher encouraged the participant to postpone testing to a later date when these symptoms had disappeared.

SESSION II: EXPERIMENTATION - EXPERIMENTAL CONDITIONS 1 AND 2

As conditions 1 and 2 were identical, with the only difference represented by the number of runs required during each over, the protocol is first described generally and then at the end of this section differences between the two are highlighted.

Players were tested individually during each of the experimental sessions. At the onset of the session, players were fitted with a Polar heart rate monitor and watch. Players were then required to lie in a supine position during which reference heart rate was obtained. In order to assess muscle activity of the quadriceps and hamstring musculature, electrodes were placed on the dominant limb of all participants. The specific placement was determined by the player contracting each individual muscle group by performing specific movements to isolate each muscle, and through palpation by the researcher. The area where the electrodes were to be attached were then shaved with a disposable razor, and cleaned with an alcohol swab to ensure good connectivity. Following this, the EMG electrodes were attached to the dominant lower limb of the player in the direction of the muscle fibres, positioned in such a way so as to limit interference from surrounding muscles and ensure good connectivity from the muscles concerned. Players were then required to participate in a cricket-specific warm up including stretching, administered by the researcher, in order to minimise the risks of injury during the session, and only following this did testing commence. As water loss was not a focal point of the study, players were encouraged to maintain water intake as required throughout both experimental conditions.

Players were then required to undergo strength testing through isokinetic dynamometry. Players were instructed to perform the pre-protocol eccentric and concentric knee flexion and extension exercises on an isokinetic dynamometer, the CYBEX 6000. The dominant leg of each participant was utilised for this testing station, and the order of protocol administration was randomised. Three repetitions were performed at each speed, $60°.s^{-1}$ and $270°.s^{-1}$, with a 30 second rest period between each set. Following the isokinetic testing, players were required to perform the three minute EMG protocol designed by Rahnama *et al*. (2006) (Table III, pg 44). Players were required to randomly walk, jog, stride and sprint on instruction, as the speeds altered. This protocol was completed twice during each condition (pre- and post-protocol), and a treadmill was used in order for the speeds to be controlled manually.

On completion of the first bout of strength testing, players were requested to pad up in full batting kit, as in a match scenario, in preparation for the batting-specific protocol. During this protocol, six balls were faced for a total of seven overs (total of 42 balls). Depending on the condition, players were required to maximally sprint a double shuttle run either following every ball delivered (high-volume running condition), or following every second delivery (moderate-volume running condition). This represents the only difference between conditions. The distance of a single shuttle sprint is 17.68 meters, representing the distance between the two creases on a cricket pitch. Both conditions ensured a break of 32.67 seconds between each delivery, and 79.80 seconds between each over. These times allowed for the recording of the physiological (heart rate) and perceptual (RPE and body discomfort) data collected on the completion of each over. The sprint time of each player was monitored by an LED system connected to a timer; as the beam was broken, indicating the player had initiated the double shuttle sprint, the timer was initiated, and following the second break in the beam, the timer was terminated and the value recorded (in seconds). On completion of all seven overs, the player was allowed to remove the cricket kit. Participants then performed the second bout of isokinetic strength testing, where once again the maximum concentric and eccentric knee flexion and extension exercises were performed. Following this, the three minute EMG protocol developed by Rahnama *et al*. (2006) was repeated. On completion, all remaining equipment was removed from the players, and each participant was then required to partake in a cool down session, which included stretching, to minimise any discomfort following the experimentation process.

STATISTICAL ANALYSES

Statistical analyses were performed using Statistics software (StatSoft, Inc. (2011) STATISTICA©. Version 10.0). Prior to any statistical analyses, descriptive analyses and tests to determine normal distribution were conducted using STATISTICA. Two-way Analyses of Variance (ANOVA) with repeated measures were then used to identify statistically significant changes in musculoskeletal, physiological and perceptual measures between protocols. A p-value less than 0.05, associated with a confidence interval of 95%, indicated significant change for each variable. Tukey *post-hoc* multiple comparison tests were performed where these significant differences were identified, serving to highlight where the significance was situated from the interactions between conditions and over time.

CHAPTER IV

RESULTS

INTRODUCTION

The purpose of this investigation was to compare the changes in muscle activity, as well as the eccentric and concentric force production of the quadriceps and hamstring muscle complexes following a batting-specific work bout at two varying intensities. A group of trained players (n=20), categorised as specialist batsmen, performed both a high- and moderate-intensity condition, the results of the comparison of which are to follow. Importantly, players were required to complete a perceptual scale relating to delayed onset muscle soreness (DOMS) prior to the onset of both the high- (HVR) and moderate-volume running (MVR) conditions; no DOMS was reported by any participant prior to either condition.

BASELINE MEASURES

Table IV: Mean of selected baseline measures collected prior to testing.

	Mean	**SD**	**CV**
Age (years)	22.60	4.74	21
Stature (cm)	179.51	6.38	4
Mass (kg)	80.77	11.77	15
Body Mass Index (kg.m^{-2})	25.08	3.73	15
Mass of Kit (kg)	4.46	0.30	7
Sum of Seven Skinfolds (mm)	82.77	29.77	36
Body Fat percentage (%)	11.29	4.63	41

SD = Standard Deviation; CV = Coefficient of Variation (%)

A total of twenty cricket batsmen, with a mean age of 22.6 (± 4.74) years agreed to participate in the study. Table IV indicates a low variability within all baseline measures excluding sum of skinfolds and body fat percentage. The mass of the kit ranged from 3.88 to 4.98kg; this range falls within the acceptable limit of less than 20 percent body mass for what has been referred to as ‘energetic free ride’ (Maloiy *et al*., 1986).

PHYSIOLOGICAL PARAMETERS

HEART RATE

Mean heart rate responses recorded prior to the onset of both the HVR and MVR conditions were statistically similar ($p>0.05$) (Figure 6). The pattern of heart rate (HR) responses for both conditions was similar (Figure 6).

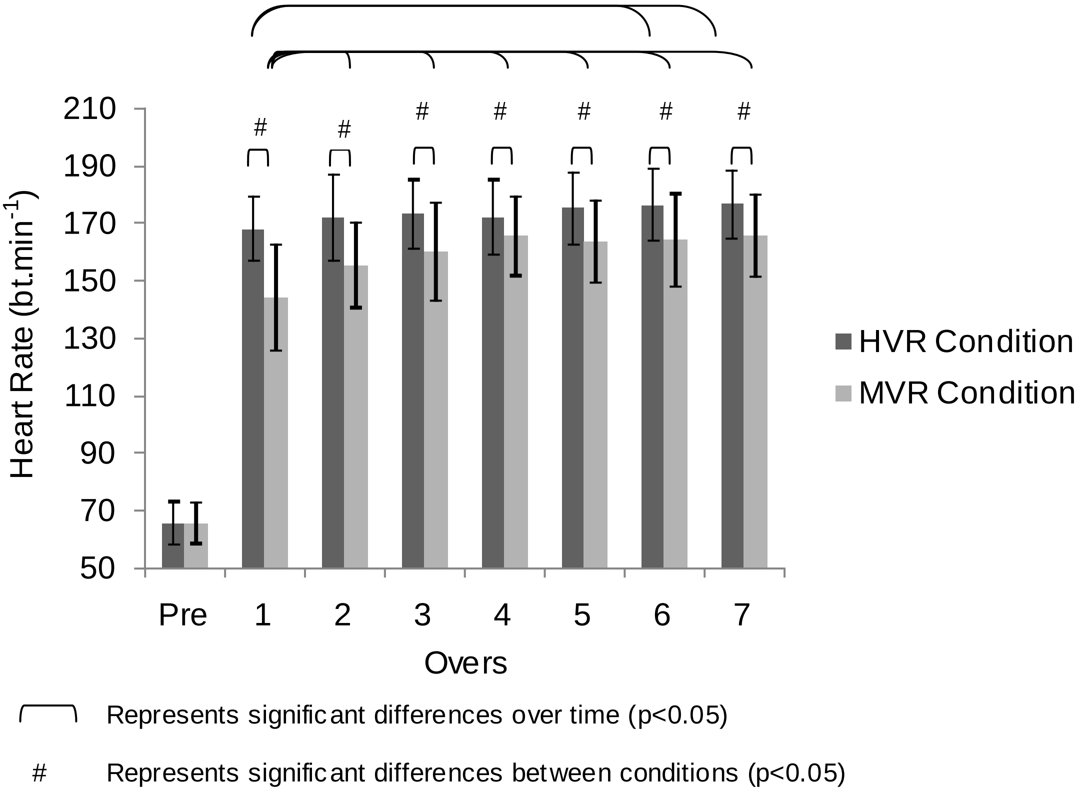


Figure 6: A comparison of the mean (±SD) heart rate responses over time in the two conditions.

A significant ($p<0.05$) increase was observed between the transition from rest to exercise within both conditions. A perceived steady state (SS) was reached at similar time intervals in both the HVR and MVR conditions (overs three to seven); the mean values recorded during this period corresponded to 89% (HVR) and 83% (MVR) of the mean player's age-predicted heart rate maximum. HR responses were significantly ($p<0.05$) higher at all time intervals during the HVR condition than the MVR condition. Further significant ($p<0.05$) increases were observed over time within both conditions, from the first to the final two overs in the HVR condition (168 ± 11.32 to 176 ± 12.44 and 176 ± 11.83 bt.min^{-1} respectively), and from the first to all other time intervals in the MVR condition.

BIOPHYSICAL PARAMETERS

ELECTROMYOGRAPHY

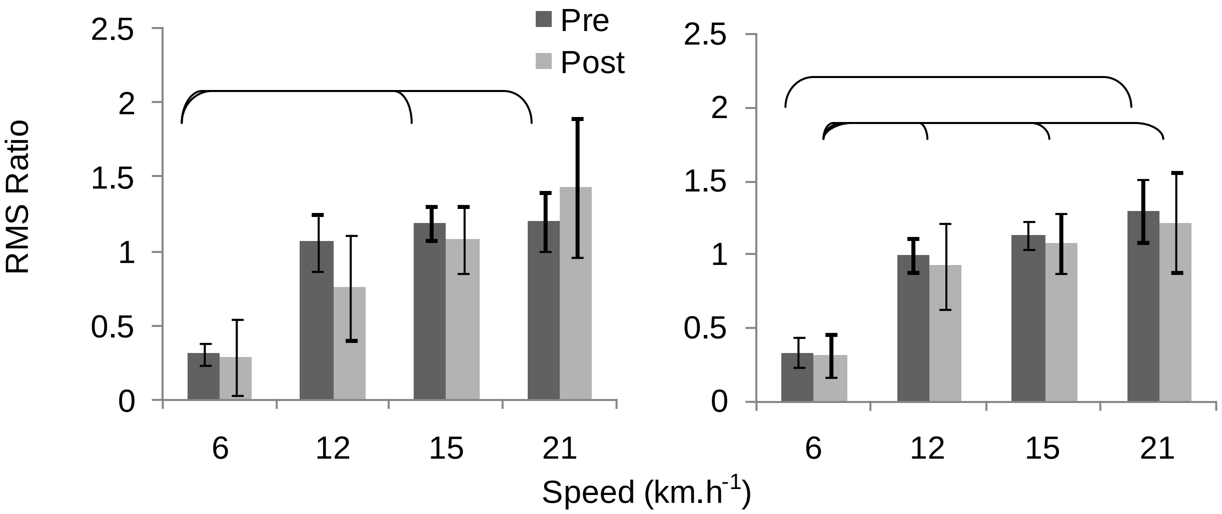
An increase in the root mean square (RMS) as running speed increased was observed in the lower limb musculature during the EMG treadmill normalization protocol (Table III, pg 44). However, the RMS decreased following each respective work bout. This statement holds true for all muscles following the MVR condition, but only for the semitendinosus following the HVR condition. Due to the large number of significant differences, these are not shown in Table V; refer to Appendix C (pg 142) for significance table.

Table V: Changes in RMS values at each speed during the EMG protocol for the quadriceps and hamstring musculature following both the high- and moderate-volume condition.

Condition		Speed (km.h^{-1})	Muscle			
			VM	**VL**	**BF**	**ST**
High-volume condition	**Pre**	**6**	0.32	0.55	0.54	0.6
		12	1.07	0.52	0.59	0.81
		15	1.2	1.18	0.85	1.01
		21	1.21	1.2	0.94	1.09
	Post	**6**	0.3	0.26	0.17	0.21
		12	0.77	0.87	0.51	0.27
		15	1.09	1.01	0.61	0.17
		21	1.44	1.1	0.95	0.3
Moderate-volume condition	**Pre**	**6**	0.34	0.41	0.39	0.36
		12	0.99	1.03	0.96	0.96
		15	1.23	1.11	1.01	1.07
		21	1.3	1.41	1.53	1.45
	Post	**6**	0.31	0.27	0.2	0.28
		12	0.92	0.85	0.64	0.92
		15	1.08	0.91	0.66	0.99
		21	1.22	1.07	1.27	1.32

Where: VM = vastus medialis; VL = vastus lateralis; BF = biceps femoris; ST = semitendinosus

QUADRICEPS MUSCULATURE



(A) **(B)**

Represents significant differences between speeds ($p<0.05$)

Figure 7: The mean (±SD) RMS ratio (referenced to all speeds performed prior to each condition) highlighting muscle activation within the vastus medialis (VM) muscle during the high- (**A**) and moderate-volume condition (**B**).

Although no significant differences were observed in quadriceps EMG between conditions or ‘pre’ and ‘post’, significant ($p<0.05$) increases in muscle activation were noted within the HVR and MVR conditions. Within the ‘pre’ HVR protocol, significance was identified from speeds of 6 to 15 and 21km.h^{-1} (Figure 7A), while within the ‘pre’ values of the MVR condition, this was between 6 and 21km.h^{-1} (Figure 7B). Furthermore, significant ($p<0.05$) increases were highlighted between each speed of the ‘post’ MVR protocol (Figure 7B).

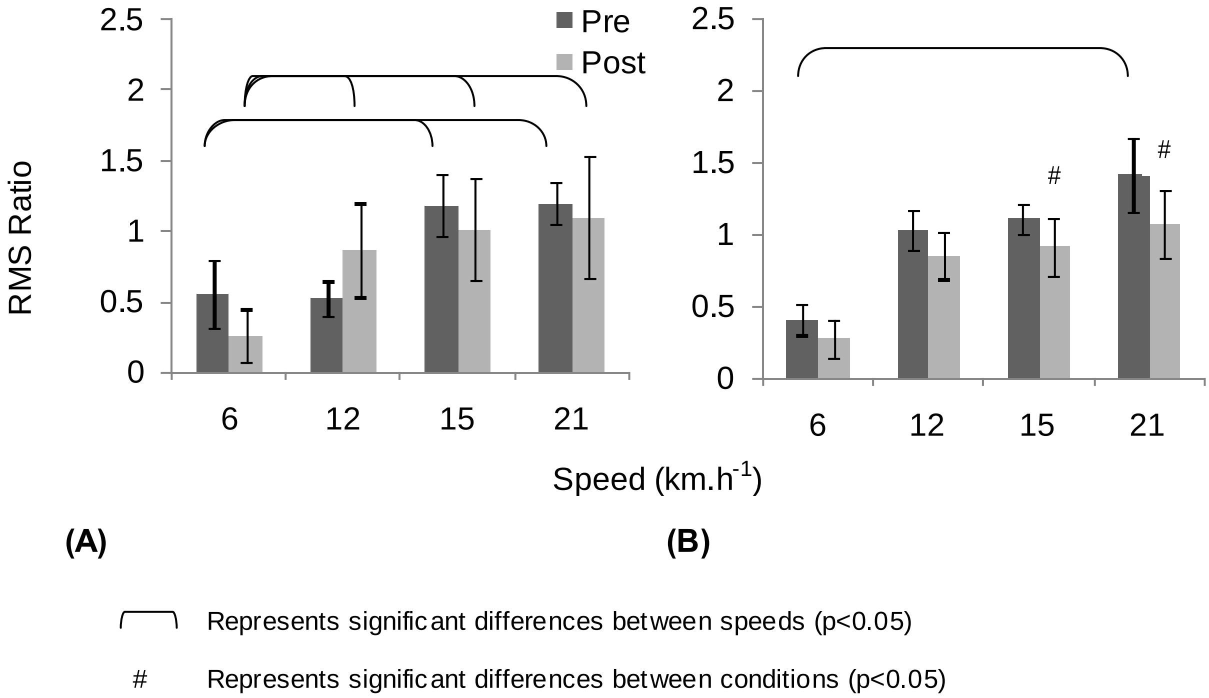


Figure 8: The mean (±SD) RMS ratio (referenced to all speeds performed prior to each condition) highlighting muscle activation within the vastus lateralis (VL) muscle during the high- (**A**) and moderate-volume condition (**B**).

With respect to the VL activation, there were significantly ($p<0.05$) lower RMS values following the MVR condition when compared to the HVR condition at speeds of 15 and 21km.h^{-1} (Figure 8B). However, there were no significant changes in VL activation following either work bout. Further significant ($p<0.05$) changes within each condition occurred with an increase in the 'pre' RMS values from 6 to 15 and 21km.h^{-1}, as well as an increase within the 'post' values at each speed following the HVR condition (Figure 8A). The only significant ($p<0.05$) difference observed within the MVR condition was between 'pre' RMS values at speeds of 6 and 21km.h^{-1} (Figure 8B).

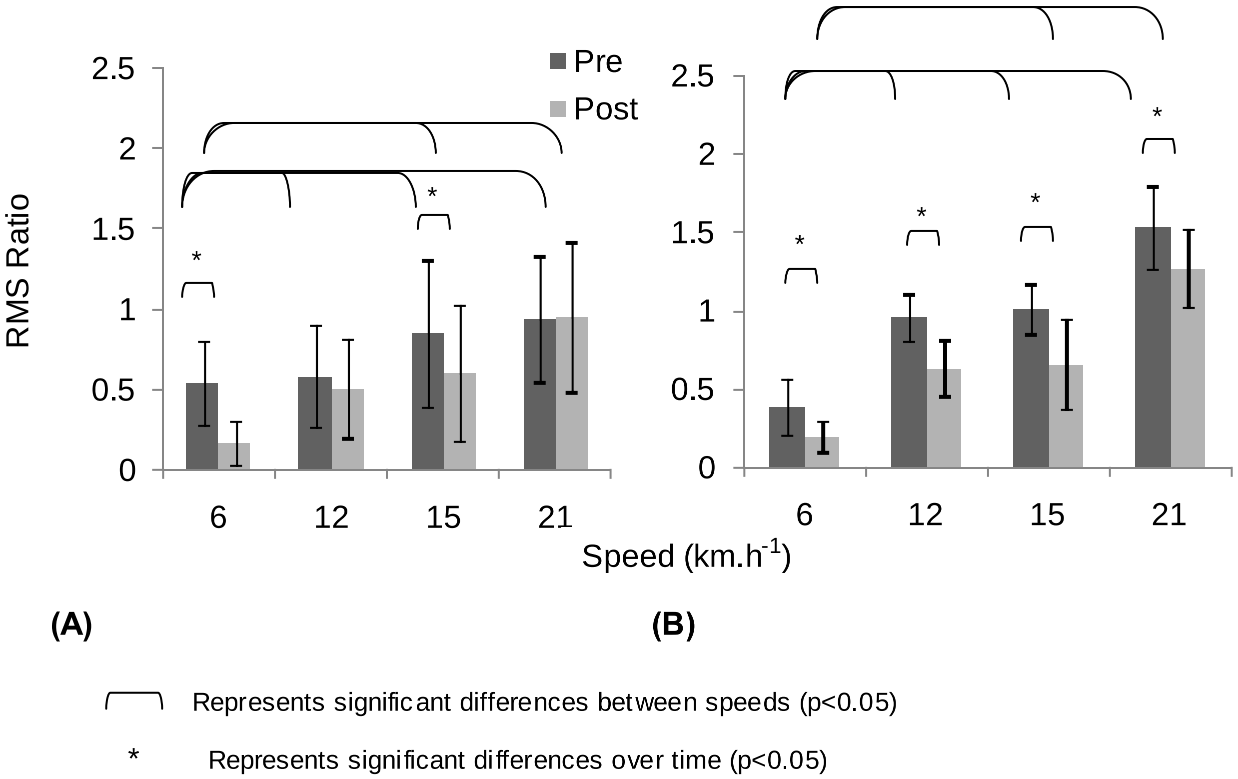
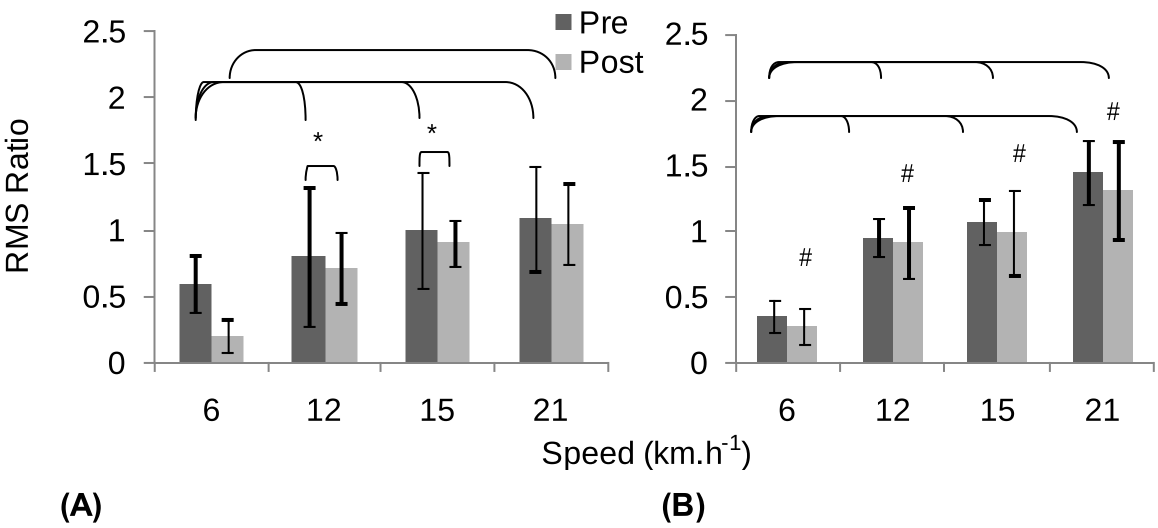


Figure 9: The mean (±SD) RMS ratio (referenced to all speeds performed prior to each condition) highlighting muscle activation within the biceps femoris muscle during the high- (**A**) and moderate-volume condition (**B**).

No significant differences (p>0.05) were observed between the HVR and the MVR conditions (Figure 9A and B). During the HVR condition there were significant (p<0.05) reductions in biceps femoris activation between the ‘pre’ and ‘post’ data at speeds of 6 and 15km.h^{-1} (Figure 9A), whereas significant (p<0.05) reductions were observed at all speeds between the ‘pre’ and ‘post’ RMS ratios within the MVR work bout (Figure 9B). Furthermore, significant (p<0.05) increases in activation levels were observed as a function of speed in all ‘pre’ RMS ratios, and between speeds of 6, 15 and 21km.h^{-1} in the ‘post’ values of both conditions (Figure 9A and B).



╭─╮ Represents significant differences between speeds (p<0.05)

* Represents significant differences over time (p<0.05)

Represents significant differences between conditions (p<0.05)

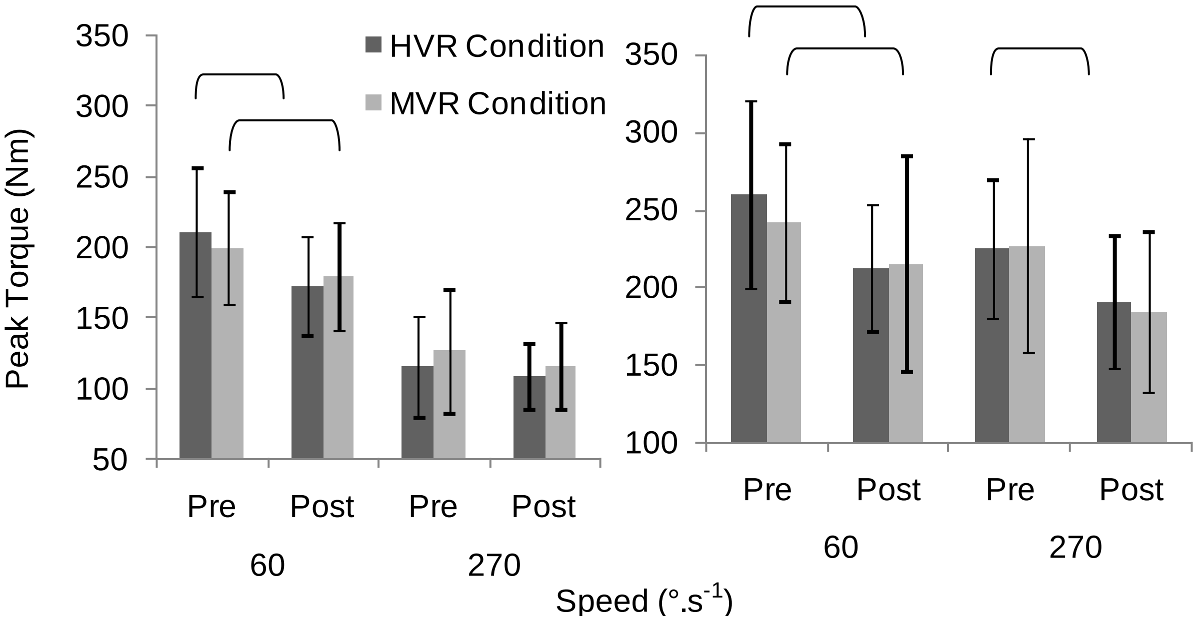
Figure 10: The mean (±SD) RMS ratio (referenced to all speeds performed prior to each condition) highlighting muscle activation within the semitendinosus muscle during the high- (**A**) and moderate-volume condition (**B**).

Significantly ($p<0.05$) higher semitendinosus activation was observed at all speeds in the ‘post’ RMS ratios of the MVR condition (Figure 10A and B). Significantly lower muscle activation was however observed when comparing the ‘pre’ and ‘post’ RMS ratios within the HVR protocol at speeds of 12 and 15km.h^{-1} (Figure 10A). No further differences were observed between the ‘pre’ and ‘post’ data within the MVR condition. Significant ($p<0.05$) increases in muscle activation were observed with an increase in speed in both conditions. The HVR work bout resulted in significant ($p<0.05$) increases at all speeds within the ‘pre’ RMS values, however differences were only observed between speeds of 6 and 21km.h^{-1} in the ‘post’ HVR condition values (Figure 10A). The MVR protocol elicited significant ($p<0.05$) increases in muscle activation at all speeds within both ‘pre’ and ‘post’ RMS ratios.

ISOKINETIC STRENGTH

QUADRICEPS – EXTENSORS

Peak Torque



(A) **(B)**

Represents significant differences over time ($p<0.05$)

Figure 11: Comparison of mean (±SD) peak torque (Nm) for concentric (**A**) and eccentric (**B**) extensors.

No differences in either concentric or eccentric peak torque were noted between the two conditions at any of the speeds (Figure 11A and B). There was however a significant ($p<0.05$) decrease in the quadriceps concentric and eccentric peak torque at 60°.s^{-1} (Figure 11A and B), more specifically, a reduction of 17.17% in concentric peak torque, and a 16.07% reduction in eccentric torque as a consequence of the twelve sprints per over (Table VI). Lower decrements of 9.36% concentrically and 7.91% eccentrically were observed when the reduced number of sprints were required. In addition, a speed of 270°.s^{-1} resulted in a significant decrement of 13.99% in eccentric peak torque values following the HVR condition (Figure 11B, Table VI).

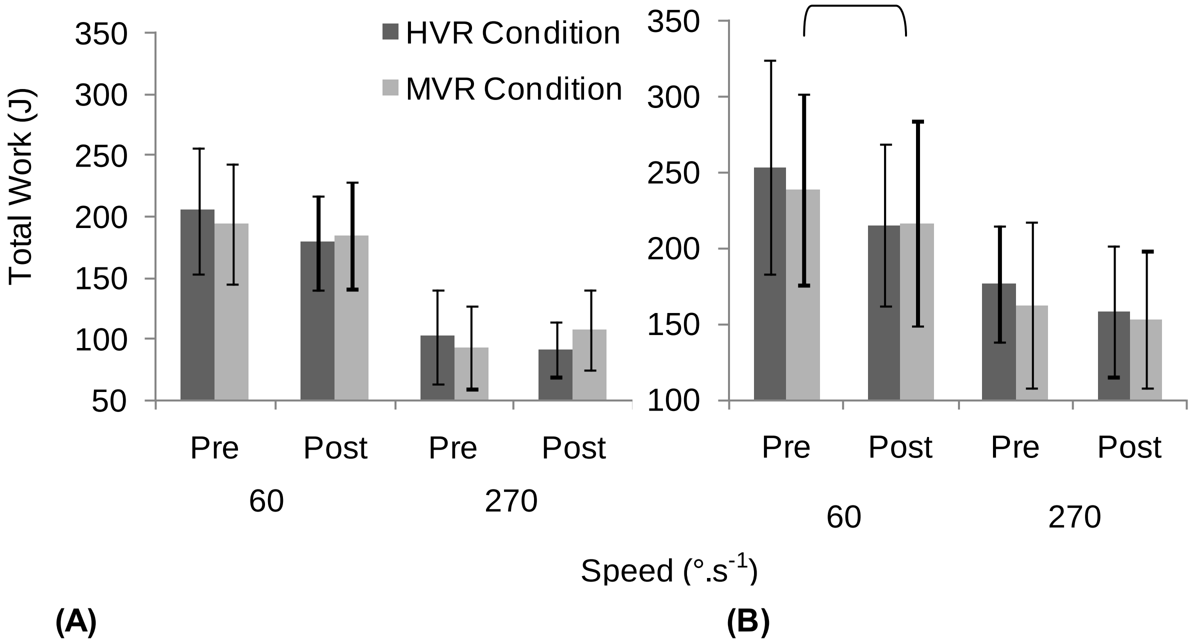
Table VI: Percentage (%) decrease in peak torque values of the quadriceps musculature as a result of the work bouts.

	Speed (°.s^{-1})	Concentric	Eccentric
High-Volume	60	17.17 *	16.07 *
	270	1.13	13.99 *
Moderate-Volume	60	9.36 *	7.91 *
	270	2.56	15.33

Where yellow represents decrements over 10% and red represents decrements over 15%

* Indicate significant ($p<0.05$) decrements represented in Figure 12

Total Work



Represents significant differences over time ($p<0.05$)

Figure 12: Comparison of mean (±SD) total work (J) for concentric (**A**) and eccentric (**B**) extensors.

No difference in the total work produced was observed between the two conditions at any of the speeds, either concentrically or eccentrically (Figure 12A and B). There was a significant ($p<0.05$) decrease in the quadriceps eccentric total work of 15.87% at 60°.s^{-1} as a consequence of the twelve sprints per over (Figure 12, Table VII).

Table VII: Percentage (%) decrease in total work values of the quadriceps musculature as a result of the work bout.

	Speed (°.s^{-1})	Concentric	Eccentric
High-Volume	**60**	13.74	15.87 *
	270	0.78	9.91
Moderate-Volume	**60**	5.05	11.48
	270	4.49	6.87

Where yellow represents decrements over 10% and red represents decrements over 15%

* Indicate significant ($p<0.05$) decrements represented in Figure 13

Total work produced is highly dependent on the range of motion (ROM) during knee extension repetitions. This was not controlled and thus several players had varying ROM prior to, and following the work bout. This is evidenced by the high variability within the work measures and thus must be interpreted with caution.

Average Power

No difference in the concentric or eccentric average power was identified between both the HVR and MVR conditions at any of the speeds (Figure 13A and B). A decrement of 9.46% was observed within the concentric extensors following the MVR work bout at 60°.s^{-1}; resulting in significantly ($p<0.05$) lower average power produced (Figure 13A, Table VIII). Although the eccentric extensors had higher percentage decrements following the MVR protocol, these values resulted in a coefficient of variation greater than 20%, resulting in non-significant ($p>0.05$) results (Table VIII).

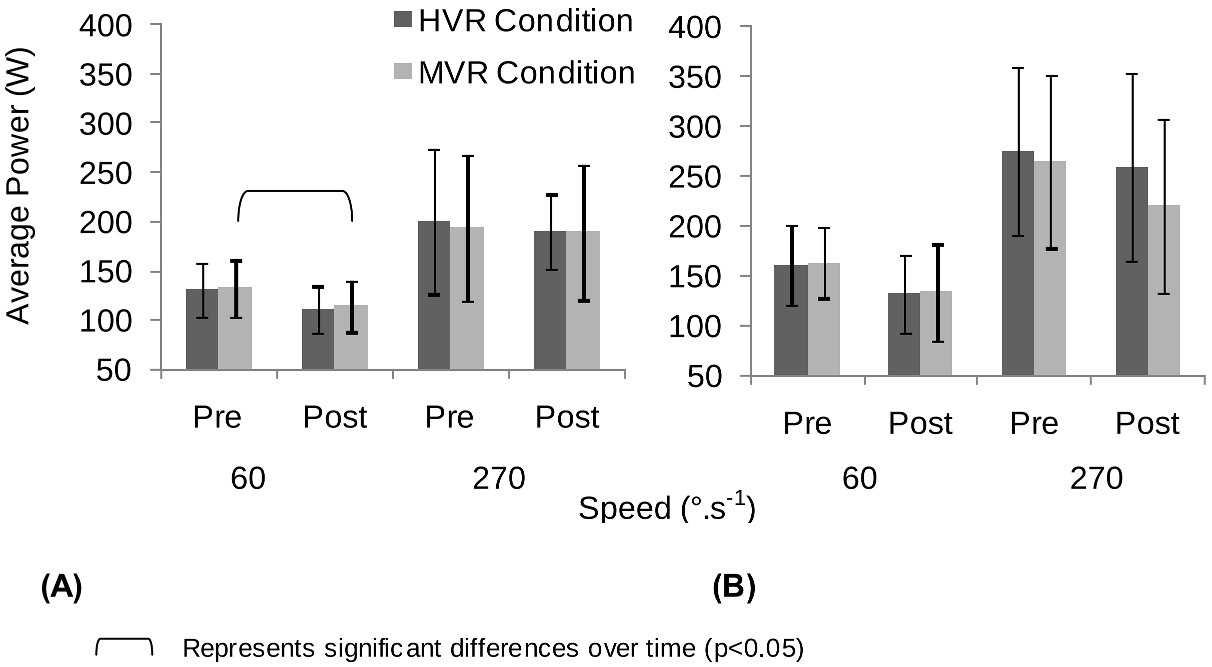


Figure 13: Comparison of mean (±SD) average power (work) for concentric (**A**) and eccentric (**B**) extensors.

Table VIII: Percentage (%) decrease in average power values of the quadriceps musculature as a result of the work bouts.

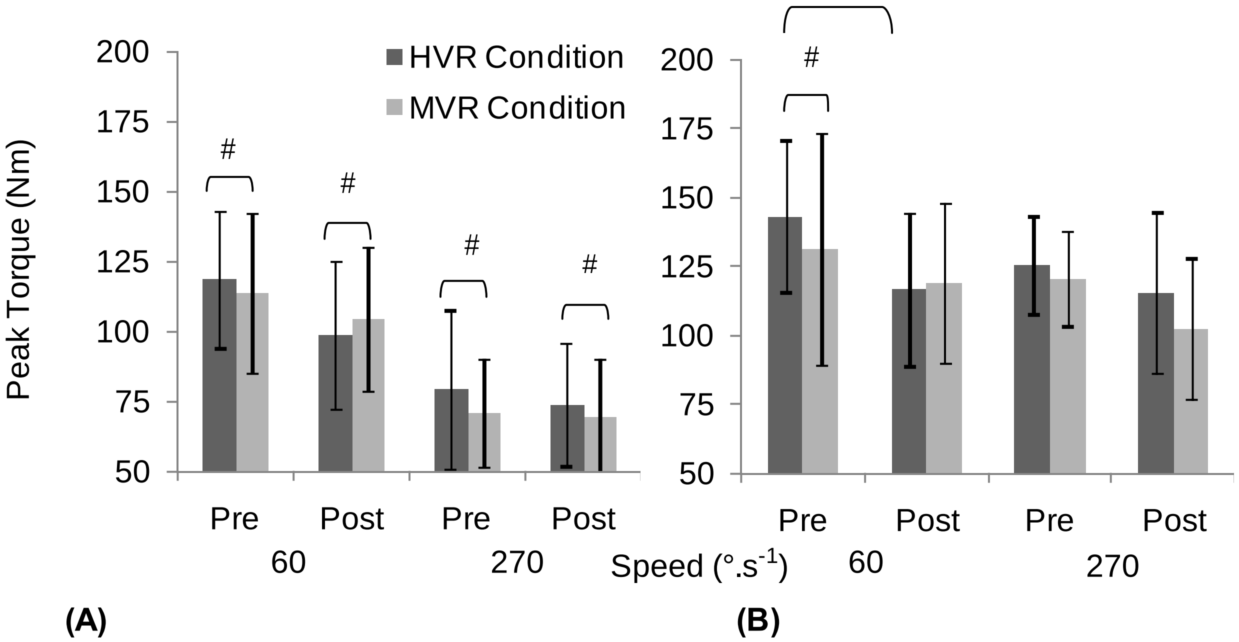
	Speed (°.s^{-1})	Concentric	Eccentric
High-Volume	**60**	5.34	🟨 12.13
	270	5.65	3.05
Moderate-Volume	**60**	9.46 *	🟥 19.12
	270	4.83	🟥 15.6

Where yellow represents decrements over 10% and red represents decrements over 15%

* Indicate significant ($p<0.05$) decrements represented in Figure 14

HAMSTRINGS – FLEXORS

Peak Torque



⊓ Represents significant differences over time ($p<0.05$)

\# Represents significant differences between conditions ($p<0.05$)

Figure 14: Comparison of mean (±SD) peak torque (Nm) for concentric (**A**) and eccentric (**B**) flexors.

Significant ($p<0.05$) differences were highlighted between the HVR and MVR conditions at both speeds within the concentric ‘pre’ and ‘post’ peak torque values (Figure 14A). However, with respect to the eccentric flexors, a significant ($p<0.05$) difference was only identified between the ‘pre’ HVR protocol and MVR protocol peak torque values at 60°.s^{-1} (Figure 14B, Table IX). Furthermore, there was a significant ($p<0.05$) 17.49% reduction in hamstring eccentric peak torque at 60°.s^{-1} following the HVR condition (Figure 14B, Table IX).

Table IX: Percentage (%) decrease in peak torque values of the hamstring musculature as a result of the work bouts.

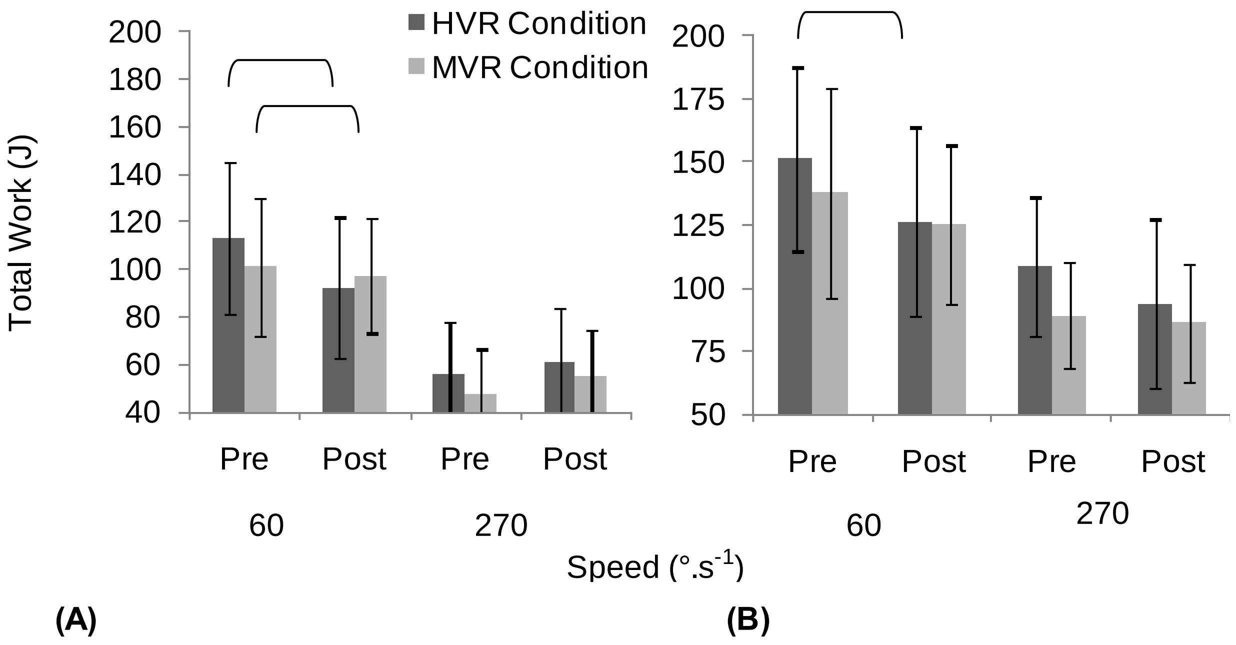
	Speed (°.s^{-1})	**Concentric**	**Eccentric**
High-Volume	**60**	16.63	17.49 *
	270	2	7.95
Moderate-Volume	**60**	1	0.82
	270	0.75	12.49

Where yellow represents decrements over 10% and red represents decrements over 15%

* Indicate significant ($p<0.05$) decrements represented in Figure 15

Total Work

As with the extensors, range of motion was not controlled resulting in a high variability of the work data. No differences were observed in the total work produced between the HVR and MVR conditions either concentrically or eccentrically at any of the speeds (Figure 15A and B). Significant ($p<0.05$) reductions of 26.31% (HVR) and 6.24% (MVR) in hamstring concentric total work produced were highlighted at 60°.s^{-1} following both conditions (Figure 15A, Table X). Furthermore a significant ($p<0.05$) reduction of 18.69% in the total work produced by the eccentric flexors at 60°.s^{-1} following the HVR condition (Figure 15B, Table X).



Represents significant differences over time ($p<0.05$)

Figure 15: Comparison of mean (±SD) total work (J) for concentric (**A**) and eccentric (**B**) flexors.

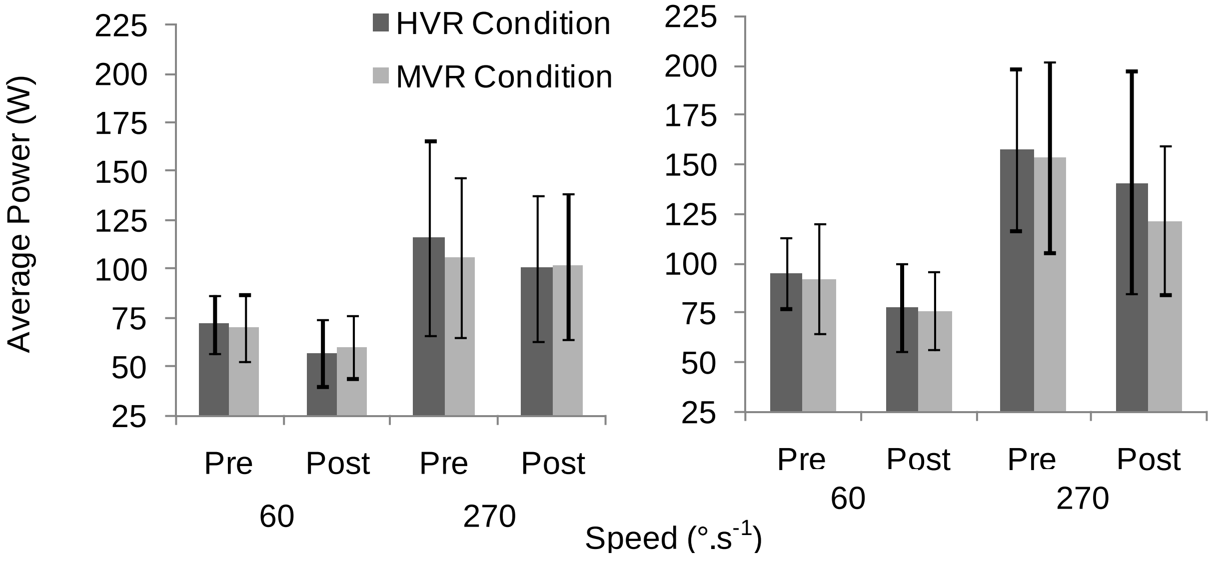
Table X: Percentage (%) decrease in total work values of the hamstring musculature as a result of the work bouts.

	Speed (°.s^{-1})	**Concentric**	**Eccentric**
High-Volume	**60**	🟥 26.31 *	🟥 18.69 *
	270	6.54	🟥 16.86
Moderate-Volume	**60**	6.24 *	🟨 13.59
	270	6.24	7.95

Where yellow represents decrements over 10% and red represents decrements over 15%

* Indicate significant ($p<0.05$) decrements represented in Figure 16

Average Power



(A) **(B)**

Figure 16: Comparison of mean (±SD) average power (work) for concentric (**A**) and eccentric (**B**) flexors.

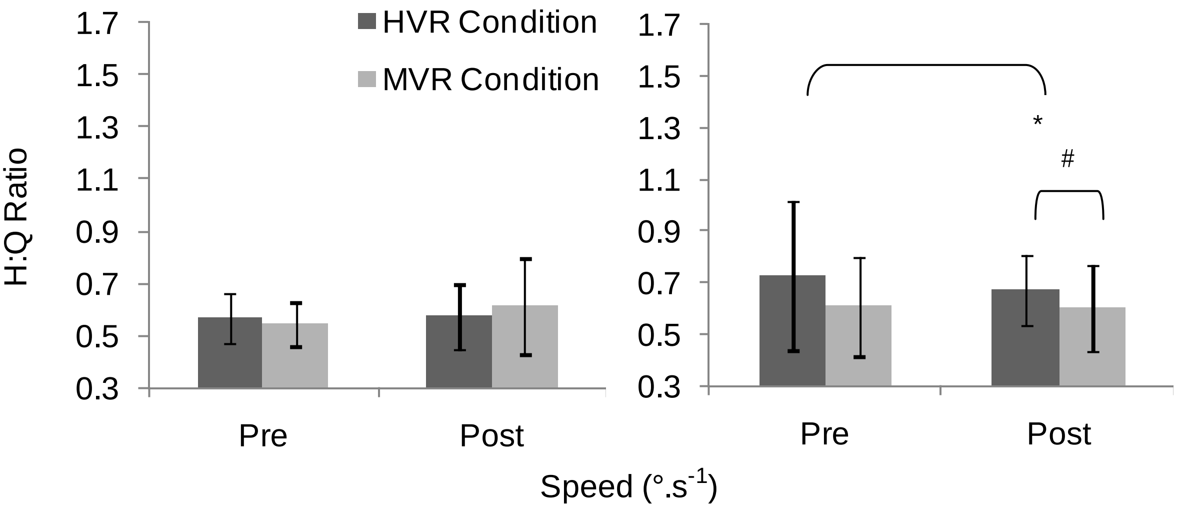
Table XI: Percentage (%) decrease in average power values of the hamstring musculature.

	Speed (°.s^{-1})	**Concentric**	**Eccentric**
High-Volume	**60**	10.23	11.96
	270	13.25	8.13
Moderate-Volume	**60**	11.31	12.21
	270	6.38	14.92

Where yellow represents decrements over 10%

No significant changes between the HVR and MVR conditions average power values were identified at any of the speeds (Figure 16A and B). Furthermore, no significant changes in the average power produced either concentrically or eccentrically by the flexors were observed over time or at any speed (Figure 16A and B).

HAMSTRING TO QUADRICEPS RATIO



(A) **(B)**

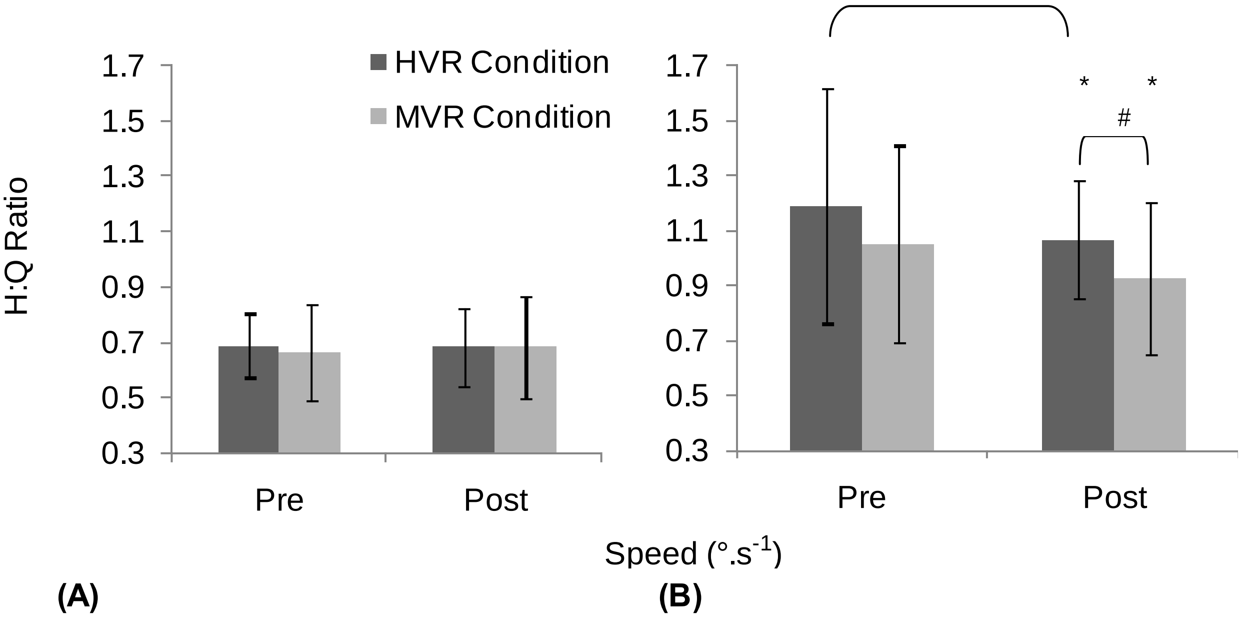
⌜⌝ Represents significant differences over time ($p<0.05$)

\# Represents significant differences between conditions ($p<0.05$)

* Represents significant differences between speeds ($p<0.05$)

Figure 17: Changes in the mean (±SD) concentric hamstring to concentric quadriceps ratio ($H_{(con)}:Q_{(con)}$) over time at $60°.s^{-1}$ **(A)** and $270°.s^{-1}$ **(B)** during both conditions.

The values produced by the conventional Hamstring:Quadriceps $H_{(con)}:Q_{(con)}$ ratio resulted in significantly ($p<0.05$) higher ratios following the HV work bout when compared to that of the MVR work bout (Figure 17B). A significant ($p<0.05$) reduction in the ratio from 0.73 (±0.29) to 0.68 (±0.13) at the speed of $270°.s^{-1}$ was observed following the HVR condition (Figure 17B). An additional significant ($p<0.05$) difference was observed between the ‘post’ ratios at the two speeds within the HVR protocol (Figure 17A and B).



⎴ Represents significant differences over time (p<0.05)

Represents significant differences between conditions (p<0.05)

* Represents significant differences between speeds (p<0.05)

Figure 18: Changes in the mean (±SD) eccentric hamstring to concentric quadriceps ratio ($H_{(ecc)}$:$Q_{(con)}$) over time at 60°.s^{-1} **(A)** and 270°.s^{-1} **(B)** during both conditions.

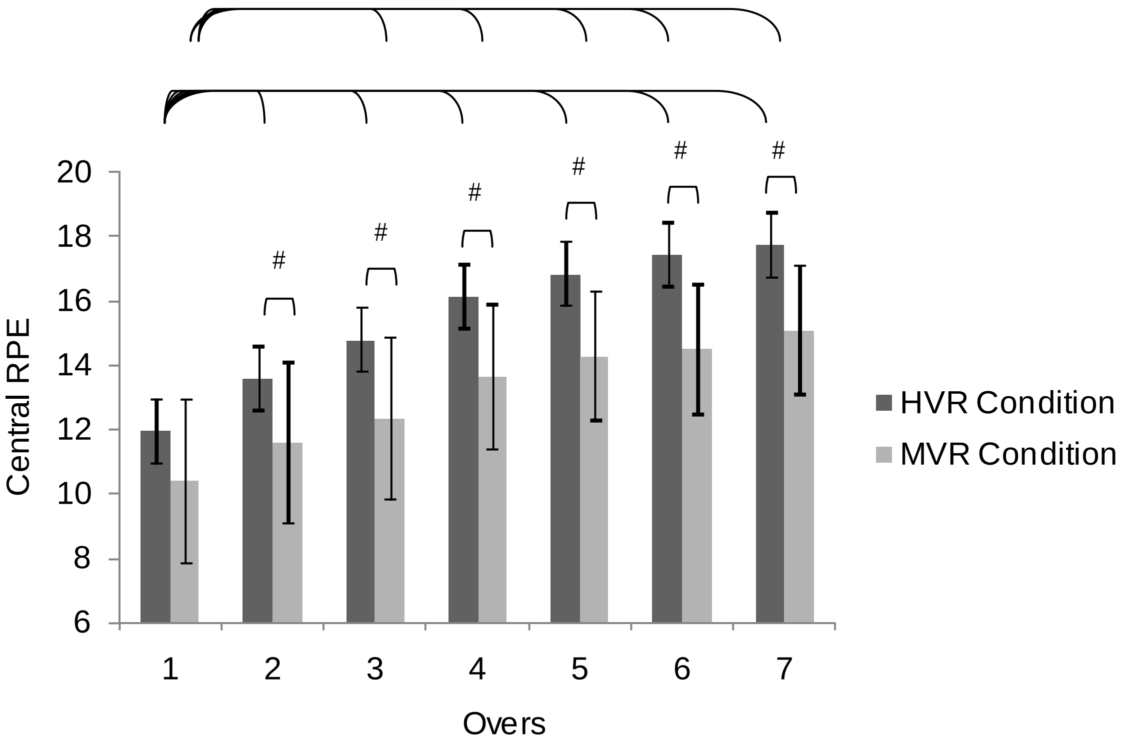
Significantly ($p<0.05$) greater $H_{(ecc)}$:$Q_{(con)}$ ratios were found following the HVR work bout when compared to that of the MVR bout (Figure 18B). More specifically, the ratios produced at speeds of 270°.s^{-1} were significantly ($p<0.05$) higher than those at 60°.s^{-1} following the HVR protocol (Figure 18A and B). Significantly ($p<0.05$) higher ratios were produced following both the HVR and MVR conditions at the functional speed when compared to those produced at 60°.s^{-1}. A significant ($p<0.05$) reduction from 1.19 (±0.43) to 1.06 (±0.21) was observed following the HVR at 270°.s^{-1} (Figure 18B).

No significant ($p>0.05$) differences were observed when comparing the $H_{(con)}$:$Q_{(con)}$ and the $H_{(ecc)}$:$Q_{(con)}$ ratios (Figure 17A and 18A), however, higher ratios overall were produced at the more functional speeds within the $H_{(ecc)}$:$Q_{(con)}$ ratio.

PERCEPTUAL PARAMETERS

RATING OF PERCEIVED EXERTION (RPE)

Central RPE



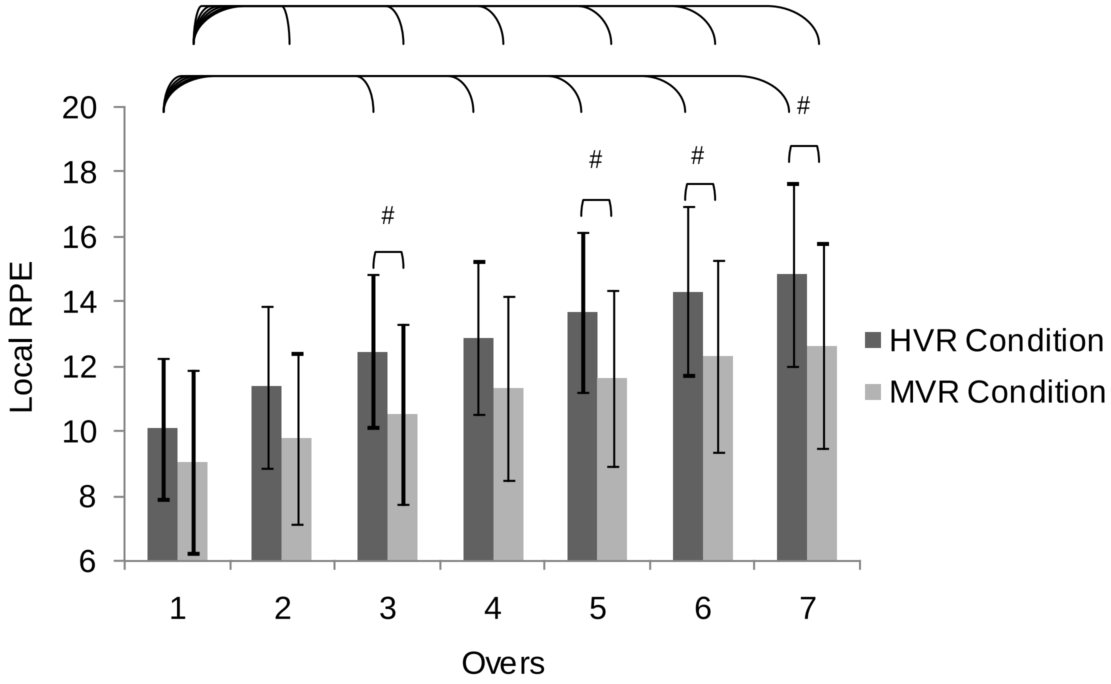
⊓ Represents significant differences over time ($p<0.05$)

\# Represents significant differences between conditions ($p<0.05$)

Figure 19: Mean (±SD) ‘central’ ratings of perceived exertion (RPE) for both conditions.

The subjective ratings of ‘central’ exertion were significantly ($p<0.05$) higher overall in the HVR condition when compared to that of the MVR condition, with greater variability within the moderate-volume ratings (Figure 19). Central RPE values displayed significant ($p<0.05$) increases over time in both conditions, more specifically, between the first and the remaining six overs in the HVR condition, and between the first over and overs three to seven in the MVR condition.

Local RPE



┌─┐ Represents significant differences over time (p<0.05)

\# Represents significant differences between conditions (p<0.05)

Figure 20: Mean (±SD) 'local' ratings of perceived exertion (RPE) for both conditions.

Although 'local' RPE displayed similar initial readings, a greater increase was observed in the high-volume condition (Figure 20). Furthermore, significant (p<0.05) increases were observed over time within both conditions, more specifically, between the first over and over's three to seven in the high-volume condition and between the first and the remaining six over's in the moderate-volume condition (Figure 20).

The subjective ratings of 'central' exertion were greater than that of 'local' exertion; there was however greater variability within the 'local' RPE responses in both conditions (Figure 19 and 20). Both 'central' and 'local' RPE were greater in the HVR condition when compared to that of the MVR condition, indicating that players perceived more strain in the former condition.

BODY DISCOMFORT

The trend of subjective discomfort ratings were an increase over time, with a greater number of reports of body discomfort following the high-volume condition (119 in total), compared to the 89 reported during the moderate-volume condition (Table XII).

Table XII: A comparison of the number of players perceiving discomfort at each time interval under the two conditions.

	High-Volume Condition							**Moderate-Volume Condition**						
Region	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Lower Back	-	-	2	3	3	5	6	-	-	1	1	1	2	2
Quadriceps	1	2	2	3	4	4	5	-	1	2	3	3	3	4
Hamstrings	1	1	2	3	4	4	5	1	1	2	2	2	2	2
Gluteal Muscles	-	-	2	2	2	2	2	-	-	-	-	-	-	-
Calves	-	-	1	1	1	1	1	-	-	-	1	1	1	1

Interestingly, the players' perceived discomfort was similar for the lower back in both conditions however the number of players perceiving this was exacerbated during the HVR condition (Table XII). In addition the quadriceps, hamstrings and calves displayed higher discomfort ratings following the HVR condition (Figure 21). Furthermore, there were no indications of discomfort in the gluteus muscles during the MVR condition yet this was the most severely rated area of discomfort in the more intense condition.

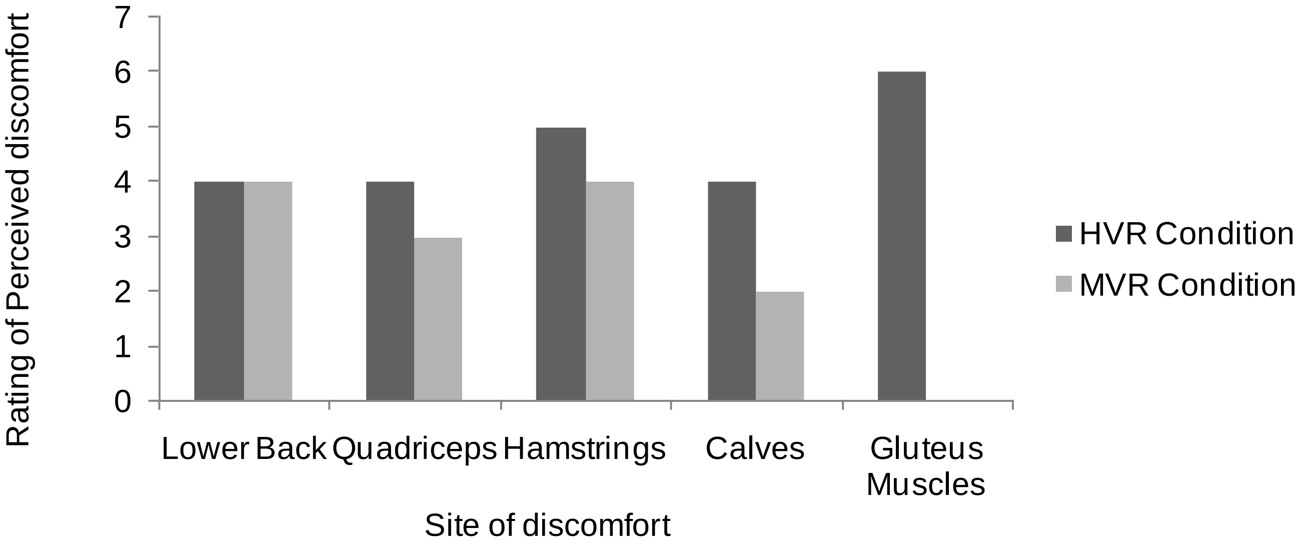


Figure 21: Perceived intensity body discomfort rating, out of a possible ten, during both experimental conditions.

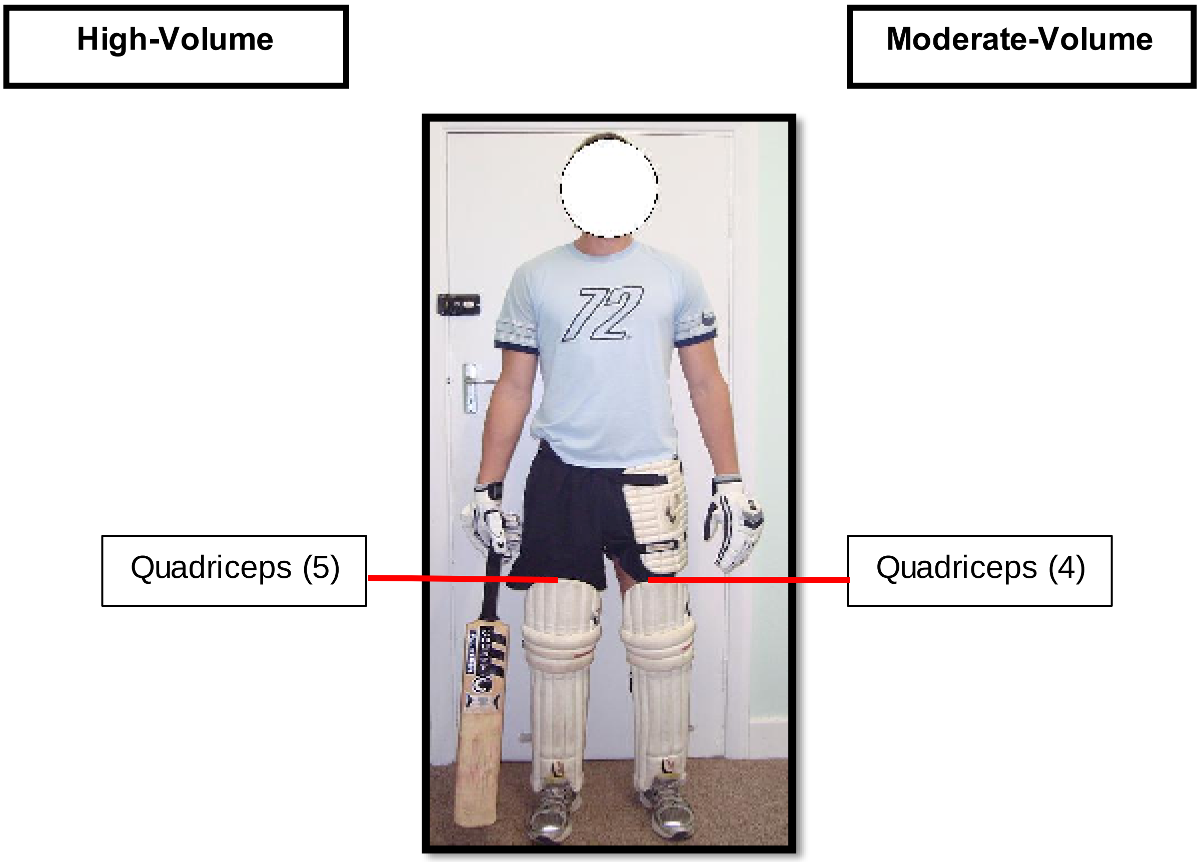


Figure 22: Anterior perceived body discomfort during the high- and moderate-volume conditions

() Indicates the number of players that reported discomfort in that area

Similar levels of anterior discomfort was identified within both conditions, indicating that irrespective of the number of repeated sprints required by the participants, the quadriceps were identified as the main area of discomfort (Figure 22). Posterior body discomfort was more commonly reported during the HVR condition, resulting in higher ratings of perceived discomfort when compared to those reported during the MVR work bout (Figure 23, Table XII). The most frequently cited area of discomfort was the lower back (6) followed by the hamstrings (5) and quadriceps (5) in the HVR work bout (Figure 22 and 23). However, of these three sites, the hamstrings corresponded with the highest ratings of discomfort (Table XII). Overall, there was more discomfort posteriorly than anteriorly.

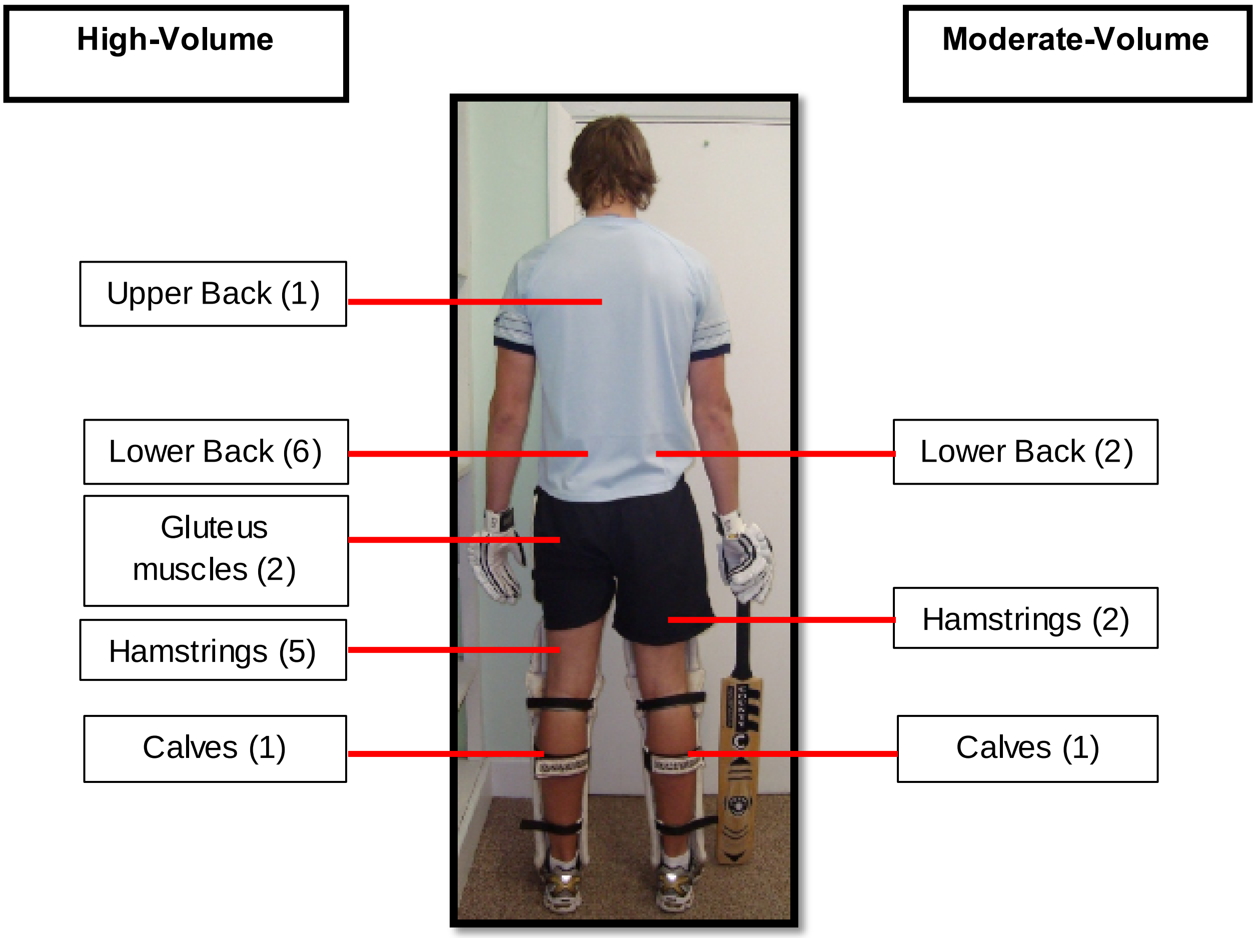


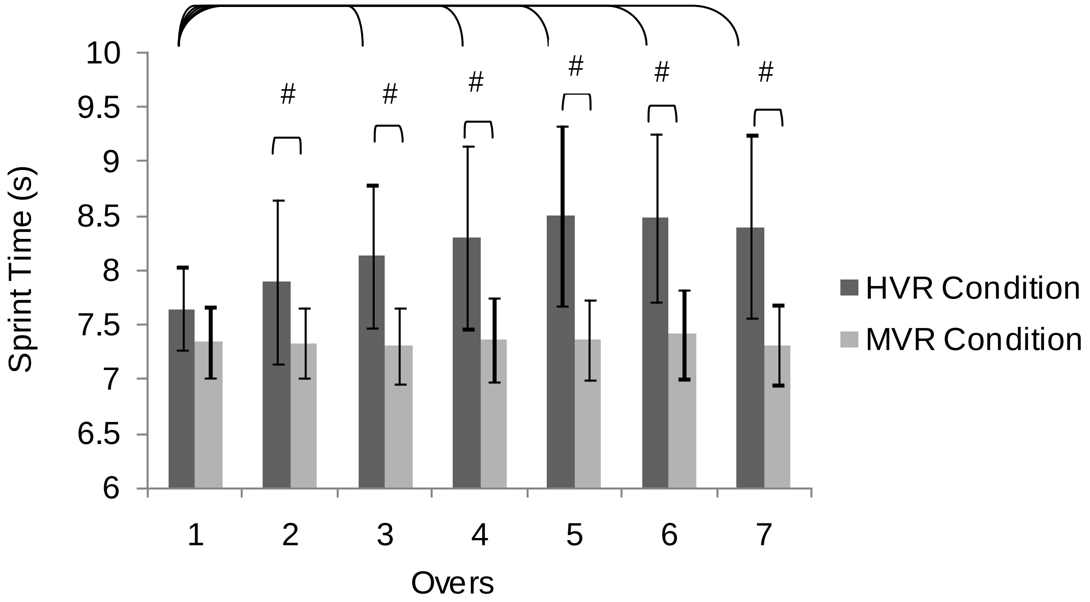
Figure 23: Posterior perceived body discomfort during the high- and moderate-volume conditions

() Indicates the number of players that reported discomfort in that area

PERFORMANCE PARAMETER

SPRINT TIMES

A similar initial sprint time was observed for both HVR and MVR conditions. Thereafter, significant (p<0.05) changes in times were observed between conditions in the remaining six overs (Figure 24). A significant (p<0.05) increase in sprint time was observed from the first over to overs three to seven during HVR work bout, 7.65 (±0.38) to 8.4(±0.84) seconds respectively, but not in the MVR work bout. In addition, the final over of both conditions displayed a non-significant increase, indicating the participants had the potential to increase their running speed in anticipation of the end point. Interesting, however, is the high variability in sprint times within the HVR condition possibly due to differences in training status or level of play. Some players thus maintained pace whereas others conserved themselves. The variability in response was less pronounced in the more conservative work bout (MVR condition).



⊓ Represents significant differences over time during the HVR condition (p<0.05)

\# Represents significant differences between conditions (p<0.05)

Figure 24: Comparison between the mean (±SD) sprint times, over time of both the high- and moderate-volume condition.

SUMMARY OF RESULTS

Higher heart rates and perceptions of effort were identified throughout the HVR condition when compared to the MVR condition. Muscle activity displayed varying results, with a trend towards increased quadriceps activation as a consequence of the HVR condition and decreased hamstring activation as a consequence of both work bouts. Performance was compromised following HVR condition but not the MVR condition. Table XIII and XIV display the condition effects and the time effects respectively.

Table XIII: All parameters displaying significance ($p<0.05$) between conditions.

PARAMETER	SITE OF P<0.05	SIGNIFICANT DIFFERENCE (P<0.05)
HEART RATE	**N/A**	HVR greater at all time intervals (overs 1 to 7)
CENTRAL RPE	**N/A**	HVR greater at overs 2 to 7
LOCAL RPE	**N/A**	HVR greater at overs 3, 5,6 and 7
EMG	**VL**	Post HVR values greater at running speeds (15 and 21km.h^{-1})
	ST	Post MVR values greater at all speeds (6, 12, 15 and 21km.h^{-1})
FLEXOR PEAK TORQUE	**CONC**	HVR greater at Pre 60, 270 and Post 270°.s^{-1} MVR greater at Post 60°.s^{-1}
	ECC	HVR greater at Pre 60°.s^{-1}
SPRINT TIMES	**N/A**	HVR slower at overs 2 to 7
H : Q RATIO	**H_{CON}:Q_{CON}**	HVR greater at Post 270°.s^{-1}
	H_{ECC}:Q_{CON}	HVR greater at Post 270°.s^{-1}

Table XIV: Parameters displaying significance ($p<0.05$) over time within each condition.

PARAMETER		SIGNIFICANT DIFFERENCE ($P<0.05$)
HEART RATE	**N/A**	Increase from rest to exercise 1st over significantly lower than overs 6 and 7 (HVR) Significant difference between all overs (MVR)
CENTRAL RPE	**N/A**	Significant increase over time from overs 1 to 7 (HVR) and overs 1 to 3, 4, 5, 6 and 7 (MVR)
LOCAL RPE	**N/A**	Significant increase over time from overs 1 to 3, 4, 5, 6 and 7 (HVR) and 1 to 7 (MVR)
EMG	**BF**	Significant decrease pre to post at speeds of 6 and 15km.h^{-1} (HVR) Significant decrease pre to post at all speeds (MVR)
	ST	Significant decrease pre to post at speeds of 12 and 15km.h^{-1} (HVR)
EXTENSOR PEAK TORQUE	**CONC**	Significant decrease pre to post at 60°.s^{-1} (HVR and MVR)
	ECC	Significant decrease pre to post at 60°.s^{-1} (HVR and MVR) Significant decrease pre to post at 270°.s^{-1} (HVR)
EXT. TOTAL WORK	**ECC**	Significant decrease pre to post at 60°.s^{-1} (HVR)
EXT. AVG POWER	**CONC**	Significant decrease pre to post at 60°.s^{-1} (MVR)
FLEXOR PEAK TORQUE	**ECC**	Significant decrease pre to post at 60°.s^{-1} (HVR)
FLEX. TOTAL WORK	**CONC**	Significant decrease pre to post at 60°.s^{-1} (HVR and MVR)
	ECC	Significant decrease pre to post at 60°.s^{-1} (HVR)
SPRINT TIMES	**N/A**	Significant increase over time from overs 1 to 3, 4, 5, 6 and 7 (HVR)
H : Q RATIO	$H_{CON}:Q_{CON}$	Significant decrease pre to post at 270°.s^{-1} (HVR)
	$H_{ECC}:Q_{CON}$	Significant decrease pre to post at 270°.s^{-1} (HVR)

CONCLUSION

The physiological and perceptual measures followed a similar trend for both the HVR and MVR conditions, although responses were consistently elevated in the HVR condition. After the first shuttle, sprint times were slower during the HVR condition while the improved sprint times in the final over of both conditions suggest that the players had the ability to increase speed. Despite players being told to give an all-out effort with each shuttle and being verbally encouraged to do so, heart rates and perceptions of effort did not reflect this providing further evidence that players' were conserving themselves. Recruitment of the hamstring musculature dropped in both conditions over time although this was more pronounced in the HVR condition. This may be an indication of fatigue suggesting a higher risk of injury to the hamstrings when sprinting between the wickets is required. Noteworthy were the large number of strength decrements following both conditions. Overall there was more eccentric changes following both conditions in both the quadriceps and hamstring musculatures. However, the greatest decrement measured was in the concentric work of the hamstrings following the HVR condition (26.31% drop). It is thus probable that the batsmen were regulating their performance based on hamstring fatigue as opposed to other responses.

CHAPTER V

DISCUSSION

INTRODUCTION

This study aimed to determine the specific musculoskeletal demands placed on the lower limbs of specialist batsmen, as well as the physiological and perceptual stresses induced by a high- and a moderate-volume work bout. The protocol utilised in the study involved a batting-specific work bout of seven overs, where the demands placed on batsmen when at the crease, were replicated. The short bursts of acceleratory and deceleratory movements, specific to an intermittent activity profile, such as cricket, were included in the work bout through repeated sprints between the wickets. It is important to note that the participants of the study competed at a university and sub-elite level, yet the players were required to complete a protocol informed by time-motion analyses on cricketers at an elite level.

BASELINE MEASURES

Despite the fact that they were sub-elite, the sample of 20 batsmen displayed similar baseline characteristics (age, stature and body mass, Table IV, pg 54) to batsmen of other studies (Stretch, 1993; Duffield and Portus, 2007; Christie *et al*., 2008; Petersen *et al*., 2010). Body fat was higher than that reported by Petersen *et al*. (2010), but similar to Noakes and Durandt (2000) and Christie *et al*. (2008). In addition, batsmen are typically of a shorter, slighter build, with a smaller muscle and bone mass and greater relative fat mass (Stretch *et al*., 2000), as found in players involved in the current experimentation. The similarities in baseline characteristics between this study and published work indicate that the results from the current study may be compared to other cricket investigations, and where research is limited, to additional studies of an intermittent nature.

PHYSIOLOGICAL PARAMETERS

HEART RATE

The results of the current investigation suggest that heart rate (HR) responses are influenced by exercise intensity, similarly to results found in studies focusing on soccer (Drust *et al*., 2000 and Greig 2006) and tennis (Fernandez *et al*., 2006). As anticipatory heart rates were no different between conditions, this suggests that players were not more anxious prior to the HVR protocol. There was thus no increase in neural outflow in anticipation of the more demanding condition (Esposito *et al*., 2004 and McArdle *et al*., 2007). Initially, an expected significant increase in HR was observed in the transition from rest to exercise with both conditions; this was in order to meet the physiological requirements of each work bout (Morris *et al*., 1998 and McArdle *et al*., 2007). This finding is supported by the results of other intermittent sport studies (Drust *et al*., 2000 and Ferrauti *et al*., 2001). Heart rate then continued to increase in both conditions although the response was more exaggerated in the HVR condition, until a steady-state occurred between the second to the fifth over in the HVR condition (172±15 to 175±13 bt.min^{-1}), and the third to the fifth over in the MVR condition (160±17 to 164±14 bt.min^{-1}) (Figure 6, pg 55).

Heart rates were significantly higher during the HVR protocol compared to the MVR protocol. More specifically, the HVR condition elicited a 13 bt.min^{-1} higher mean HR at each respective over compared to the MVR condition. The more elevated responses following the HVR protocol were expected due to the fact that double the sprint volume was performed by the players reflecting a higher physical demand associated with high-intensity activities (Zois *et al*., 2011). What is interesting however, is that there was only a 13 bt.min^{-1} difference with double the work-load suggesting that the cardiovascular system was not as strained as the musculature, for example. Further, duration of effort in a seven over work bout does not appear to affect cardiovascular strain. The mean heart rates of 160 bt.min^{-1} (MVR) and 174 bt.min^{-1} (HVR), evident once a steady-state had been reached, are higher than previously reported during an entire one-day match, however this data represented the mean over the entire match duration, and must be highlighted during comparison (Peterson *et al*., 2010). Noteworthy however is that the MVR protocol responses exhibited similar values to those reported by Christie *et al*. (2008), where a steady-state was identified following the third over of a batting-specific protocol. Mean steady-state HR values fell into the moderate- (70-85%) and high-intensity (>85% heart rate maximum (HR_{max})) zones, within the moderate- and high-volume running conditions respectively (Coutts *et al*., 2003). In rugby and soccer activities, similar findings have been identified, with players averaging over 80% HR_{max} through the course of the match, however, if including data of an entire match duration these values may be reduced due to the lower intensity efforts (Krustrup and Bangsbo, 2001 and Coutts *et al*., 2003). In addition, HR profiles obtained during the MVR protocol were comparable to those recorded during soccer activities, more specifically; players (Esposito *et al*., 2004), and high-ranking soccer referees (Krustrup and Bangsbo, 2001). Similarly, the mean HR produced during the HVR protocol was similar to that of high-intensity soccer activity (Esposito *et al*., 2004) and further lends support to the fact that cricket is not as sedate as previously thought (Woolmer and Noakes, 2008).

Although activity duration appears not to be a contributing factor to cardiovascular strain in this investigation, it is important to acknowledge that the work bouts were only 27 minutes and it is highly probable that cardiovascular drift, due to fatigue, would occur if extended periods of batting were required (McArdle *et al*., 2007).

BIOPHYSICAL MEASURES

ELECTROMYOGRAPHY

QUADRICEPS AND HAMSTRING MUSCULATURE

It has been well documented that activities requiring quick repeated acceleration and deceleration movements result in a greater degree of eccentric muscle activity, particularly in the deceleration phase (Enoka, 1996 and Highton *et al*., 2009). These activities are representative of running between the wickets; significant changes within hamstring muscle activation in particular, were therefore anticipated. The more uniform reduction in hamstring muscle activation suggest a relationship exists between the load placed on the muscles due to the repeated acceleration and deceleration requirements, and the activation levels of the involved muscles (Greig, 2006). Expectedly within both the quadriceps and hamstring musculature, increases in RMS values were observed as a function of speed, suggesting that the players were able to alter the mechanical output in order to maintain performance through the knowledge of the protocol requirements (Billaut *et al*., 2011). These findings were in accordance to those of a soccer-specific study where the authors observed increases in activation levels of the lower limb musculature with increases in speed (Rahnama *et al*., 2006), and further support the relationship that exists between running speed and EMG muscle activity (Mizrahi *et al*., 1997 and Pincivero *et al*., 2000).

Vastus Medialis

The results suggest that neither condition significantly affected the muscle activation levels of the vastus medialis (VM). However, although non-significant, there was a trend towards an increase in VM activation following the HVR condition at 21 km.h^{-1} during the treadmill normalization protocol (Figure 7, pg 58). The increase may be explained by the onset of muscle fatigue within the lower limbs, particularly evident as a consequence of double the sprint volume required by the HVR condition. This was further supported by the absence of any disturbances to the activation levels following the MVR condition and greater strength decrements in the quadriceps following the more intense, HVR condition.

Vastus Lateralis

Speeds representing running and sprinting resulted in an increase in vastus lateralis (VL) activation, particularly following the HVR condition (Table V, pg 57). Altered skeletal muscle activation levels have been strongly associated with negative changes in exercise performance due to muscle fatigue (Billaut *et al*., 2011). These results suggest that fatigue may be particularly evident at the faster running speeds, due to the greater number of runs at high speeds during the HVR work bout. This could possibly account for the lack of changes in activity levels and the ability to maintain performance at the speeds more representative of walking and jogging. The results therefore support the presence of muscle fatigue within the VL, particularly at speeds similar to those required by the players during the work bout.

Biceps Femoris

The results for biceps femoris (BF) activation suggest the presence of muscle fatigue at all speeds (6 to 21 km.h^{-1}) following the MVR condition, yet only at 6 and 15km.h^{-1} following the HVR condition. These reductions in activation levels are associated with a concomitant decrement in voluntary force production (Kellis and Baltzopoulos, 1998), acting as a protective mechanism against injury. As changes were observed as a consequence of both conditions, it can be suggested that the BF is more sensitive to the muscle actions required during the work bouts, in particular to that of the MVR as faster sprint times were recorded throughout the more conservative protocol. This was anticipated as the hamstring musculature is responsible for controlling movement particularly during the deceleratory phase, resulting in activation alterations following both work bouts. Interestingly however, BF appears to be more sensitive to moderate intensity intermittent exercise. Similar significant reductions in BF activation levels were identified by Rahnama *et al*. (2006), where the same EMG protocol was used to determine muscle activation following a soccer-specific activity. This may provide additional support to the fact that unique activation strategies are associated with eccentric muscle actions (Enoka, 1996).

The recruitment of additional muscle fibres is known to compensate for the fatiguing active motor units resulting in either an increase in muscle activation or, alternatively, the adaptation of the locomotor style (Kellis and Baltzopoulos, 1999). This adaptation would activate alternative muscle groups to maintain the required workload, with no resultant change in the EMG activity levels of the BF muscle. Literature has further identified an increase in RMS values following repetitive exhaustive activities (Oberg, 1995; Kellis and Baltzopoulos, 1999; Yeung *et al*., 1999). Differences in protocols, such as intensity, in addition to other parameters may therefore have resulted in the reduction, rather than increase in activation (Jaskólski *et al*., 2007). Sweat build-up between the electrode and the skin may further increase the difficulty in result interpretation (Rahnama *et al*., 2006).

Semitendinosus

The results of the semitendinosus (ST) activation further suggest that the hamstring musculature, rather than the quadriceps musculature, was more sensitive to both work bouts. This is in accordance with the highly eccentric nature of the batting-specific work bouts, requiring repeated eccentric muscle actions, particularly within the hamstring muscles, to decelerate when sprinting between the wickets. The onset of fatigue in these muscles may lead to further implications of possible strength impairments (Kent-Braun, 1999). Although a lack of consistency between BF and ST muscle activation patterns have previously been documented (Pincivero *et al*., 2000), the present study identified a uniform trend.

The significant increase in ST activation following the MVR condition may suggest possible fatigue, as additional inactive motor units near the surface of the muscle may have been recruited (Vollestad *et al*., 1997). This is however unlikely, as muscle strength parameters were not as affected as during the HVR condition associated with lower muscle activation levels. However, the lower RMS values following the HVR condition at speeds of 12 and 15 km.h^{-1} (Figure 10, pg 61), may indicate the additional recruitment of slow-twitch muscle fibres, resulting in limited variation in activation levels, but still indicating the presence of muscle fatigue (Edgerton *et al*., 1996 and Jaskólski *et al*., 2007). This suggests that fatigue, due to the high musculoskeletal demands of the HVR work bout, is most prevalent at those running speeds.

ISOKINETIC STRENGTH PARAMETERS

Isokinetic peak torque, total work and average power have been identified as important factors affecting the sprinting performance and endurance of batsmen when running between the wickets. Although non-significant, all strength parameters produced greater values eccentrically than concentrically; this was in accordance with existing literature (Enoka, 1996 and Faulkner, 2003).

Peak Torque

Both the HVR and MVR conditions significantly reduced extensor peak torque concentrically and eccentrically, at 60°.s^{-1}. The HVR condition further reduced extensor peak torque eccentrically at 270°.s^{-1}, and flexor values eccentrically at 60°.s^{-1}. The HVR protocol thus had a greater impact on eccentric strength, specifically peak torque at both isokinetic speeds; a finding supported by others (Jaskólski *et al*., 2007 and Highton *et al*., 2009). In addition, as a positive relationship has been identified between sprinting performance and peak torque (Dowson *et al*., 1998), the reductions in strength following the HVR condition will negatively impact sprinting performance, evident in this investigation, and increase risk of injury (Bennell *et al*., 1998).

Significantly lower concentric and eccentric flexor peak torque values following the HVR condition at isokinetic speeds of 60°.s^{-1} indicate that the increased demands of the HVR work bout resulted in greater strength decrements than that of the MVR protocol. Conversely, the more functional speed of 270°.s^{-1} resulted in greater strength decrements following the MVR condition. Bennell *et al*. (1998) indicated that speeds of 60°.s^{-1} accentuate the presence of strength deficits, not necessarily observed at faster speeds, thereby influencing the hamstring-to-quadriceps ratio and altering the injury risk of the individual. These strength decrements suggest the onset of fatigue within the hamstring muscles as a reduction in strength, particularly peak torque, has been associated with muscle fatigue (Rahnama *et al*., 2006). Isokinetic extensor and flexor peak torque has further been identified as a major determinant of sprinting performance, particularly over short distances of 15 meters (Nunes and Coetzee, 2007). Changes in peak torque in response to each condition are therefore important as they affect the ability of the batsmen to score runs, by running between the wickets, rapidly and continuously. Additional factors such as the limited time to develop sufficient torque may have resulted in greater strength decrements observed following the MVR condition at speeds of 270°.s^{-1}. It may therefore be suggested that slower isokinetic speeds of 60°.s^{-1} may be more accurate in identifying the presence of strength decrements than the more functional speed of 270°.s^{-1}.

Total Work

Both extensor and flexor eccentric values, as well as concentric flexor total work were significantly reduced following the HVR condition at 60°.s^{-1} (Figure 12 and 15, pgs 63 and 68). This suggests that in addition to negatively impacting peak torque values, the HVR work bout influenced the total work produced by the players, decreasing the strength capabilities of the lower limbs and elevating possible injury risk. Total work produced by the concentric flexors at 60°.s^{-1} was further influenced by six runs per over, indicating that concentric flexors were vulnerable to both intermittent protocols. However, the HVR condition resulted in greater strength decrements, further supporting the fact that isokinetic speeds of 60°.s^{-1} enhance the presence of strength decrements (Bennell *et al*., 1998 and Highton *et al*., 2009). The results indicate that the hamstring musculature were particularly sensitive to the work bout of higher sprinting effort, both concentrically and eccentrically, suggesting fatigue and a greater risk of injury following the HVR condition.

Average Power

No change was observed in the concentric or eccentric flexors or extensors as a product of time following the HVR condition (Figure 13 and 16, pg 65 and 69), suggesting that the duration of the work bout did not negatively impact average power. This suggests that the rate at which the quadriceps and hamstring musculature could produce force was maintained subsequent to the HVR protocol. Although faster isokinetic speeds of 240°.s^{-1} have been associated with significant changes in power (Siqueira *et al*., 2002), no reductions were observed following either condition at 270°.s^{-1}. In contrast, speeds of 60°.s^{-1} resulted in significant reductions in concentric extensor average power values as a consequence of the MVR condition. This indicates that the rate of force production by the quadriceps musculature could not be maintained following the work bout of six runs an over and further supports the work of Glaister (2005). This indicates that repeated sprints of a moderate intensity results in strength and power deficits (Highton *et al*., 2009).

HAMSTRING:QUADRICEP RATIO

Although no differences were observed at 60°.s^{-1}, significant changes were present at the functional ratio of 270°.s^{-1}, suggesting greater insight on ratio changes, specific to each condition, may be obtained at a speed more representative of the activity in question. Similarities were observed between the conventional ($H_{(con)}$:$Q_{(con)}$) and the more functional ($H_{(ecc)}$:$Q_{(con)}$) ratios at 60°.s^{-1}, ranging from 55 to 69% and all falling within the accepted normative values (Read and Bellamy, 1990; Rosene *et al*., 2001; Coombs and Garbutt, 2002). Greater values were however, produced following the HVR work bout compared to the MVR work bout at isokinetic speeds of 270°.s^{-1}. The closer the functional H:Q ratio is to 100%, at faster speeds, indicates an enhanced ability for dynamic knee joint stabilization during forceful knee extension movements (Aagaard *et al*., 1998). This suggests that following both conditions, the hamstring musculature would provide dynamic joint stability during forceful knee extension, although this was significantly ($p<0.05$) greater following the HVR condition. The duration of the protocols must however be considered, the hamstrings may provide greater stability during high-intensity sprinting of short durations, although it could be suggested that an increase in the batting activity may negatively impact this stability and result in possible injury.

Both traditional (H_{con}:Q_{con}) and functional (H_{ecc}:Q_{con}) ratios display significant decrements following the HVR protocol at isokinetic speeds of 270°.s^{-1}. Although the functional ratio was closer to 100% indicating stability, the decrement highlights the decrease in the dynamic stability of the knee during knee extension activities as a consequence of high-volume running. An increase in exercise duration could result in further decrements, reducing the ability to stabilize the knee joint during dynamic, forceful extension activities (Aagaard *et al*., 1998). The higher decrements associated with 270°.s^{-1} suggest that a more functional speed may provide a greater understanding on functional ability and muscle balance than those observed at speeds of 60°.s^{-1}.

Similarities between the H_{con}:Q_{con} ratios recorded during this study and that of professional soccer athletes (Greig and Siegler, 2009) were observed. In contrast, Rosene *et al*. (2001), investigating university level volleyball and soccer players found lower ratios than that of the current study. The higher ratio presently observed suggests an increase in hamstring strength, possibly due to differences in training levels, or alternatively an added requirement for improved hamstring strength due to the repeated eccentric demands of a cricketing activity rather than those of other intermittent sporting disciplines. However, it must be highlighted that although studies have suggested a ratio less than 60 percent may be indicative of injury, this has yet to be fully supported (Bennell *et al*., 1998). It is therefore suggested that muscle strength decrements observed within the hamstring musculature be of greater importance than that of the ratios.

PERCEPTUAL PARAMETERS

RATINGS OF PERCEIVED EXERTION

‘Central’

The perceived ratings of effort reported by the players, particularly with reference to the cardiovascular system, further supported the greater physiological demands elicited by the HVR condition. These results are similar to those of Swart *et al*. (2012), where RPE was observed to increase in both a high- and a low-intensity cycling activity although this increase was at a slower rate during the low-intensity activity. Similarly to HR, exercise intensity was highlighted as a critical factor in determining perceived exertion, with a concomitantly higher increase in RPE following an increase in intensity (HVR protocol). The responses of perceived cardiovascular effort during the MVR condition were similar to those reported during pilot investigations in this department (Christie *et al*., 2011a and 2011b). Furthermore, when compared to soccer activities, similar ‘central’ RPE values (15) were noted on completion of the activity (Drust *et al*., 2000), increasing with elevated exercise intensities and duration (Esposito *et al*., 2004). In addition, a laboratory simulation of a one-day batting century conducted by Houghton *et al*. (2011) identified an increase in perceived strain over time, corresponding to an increase in intensity. Furthermore, the RPE values following the ‘closing the match’ stage of the innings, classified as high risk, were similar to that of the HVR condition in this study (Houghton *et al*., 2011). Despite the request for all-out effort in conjunction with the verbal motivation to do so, the perceived ratings did not reflect maximum, but voluntary effort, suggesting players were conserving themselves, particularly during the more intense condition.

The relationship between HR responses and ‘central’ RPE is well understood during intermittent exercise (Fernandez *et al*., 2006 and Tucker, 2009), with strong linear predictive abilities ($R^2=0.99$) identified by Brown and Christie (2009). It is suggested that higher ratings of effort are associated with the subconscious detection of high heart rates (De Koning *et al*., 2011). The observed relationship between ‘central’ RPE and HR in this study further supports the possibility that a similar relationship may exist during ‘stop/start’ activities. In addition, a study conducted by Zois *et al*. (2011) on soccer players highlighted a positive relationship between the level of exertion perceived by the players and cardiovascular demands, particularly during intermittent activities of a high intensity. This increase, particularly following the HVR protocol, indicates that limited recovery periods as well as the demands to maintain performance resulted in greater perceptions of effort by the players.

RPE is influenced not only by physiological factors, but by subconscious processes analysing external feedback such as exercise duration and intensity (Albertus *et al*., 2005). This feedback, known prior to the onset of the work bouts, is referred to as a feed-forward mechanism. This allowed RPE to be set during the initial overs of both conditions and subconscious regulation of variables through external feedback allowed alterations in exercise intensity in order to delay exhaustion of the players and exercise termination (Albertus *et al*., 2005). Previous experience of the activity further influenced the subjective rating expressed by the players, the memory of fatigue allowed for the estimation of reserve capacity and tolerance levels, thereby informing whether the player had capacity to continue, and in doing so, altered the RPE values (St Clair Gibson *et al*., 2003). Higher ‘central’ values reported during the HVR condition suggest a reduced reserve capacity and tolerance to the higher intensity work bout, and further indicates an increase in the magnitude of the threat imposed by this work bout (Swart *et al*., 2012).

‘Local’

The results of the current study highlight a consistently high perception of effort within the musculoskeletal system, particularly of the lower limbs following the HVR condition. It has been suggested that the brain regulates the degree of muscle activation in response to external feedback, via RPE mediation, in order to avoid detrimental physiological disturbances (Tucker, 2009). Exercise intensity was therefore further identified as a major determinant of perceived exertion within the musculoskeletal structure, in addition to that of the cardiovascular system. As the HVR protocol was associated with a greater number of repeated sprints, a resultant increase in the volume of eccentric muscle activity occurred, possibly influencing the discomfort perceived by the players (Nicol, 1991 and Byrne *et al*., 2004). Although increases in perceived exertion were documented, ‘local’ ratings were however found to be lower than the values representing ‘central’ RPE during both conditions, indicating that the participants found both conditions more taxing on the cardiovascular, rather than the musculoskeletal system.

Interestingly, although players were required to perform the repeated sprints with maximum effort, activating involved muscles to a greater degree, ratings within both the HVR condition and the MVR condition were relatively low at 10 and 9 respectively (‘fairly light’ and ‘very light’), increasing to 15 and 13 respectively (‘hard’ and ‘somewhat hard’) following the final over. RPE is determined at the onset of exercise via a feed-forward mechanism, which combines previous experience, knowledge of exercise duration prior to the onset of the protocol, as well as physiological feedback, allowing players to change sprinting performance to ensure the exercise is completed with no bodily harm, and that increases as a function of exercise duration (Albertus *et al*., 2005 and Tucker, 2009). The fact that players knew what each work bout comprised could have influenced their pacing and responses. Furthermore, it explains the non-maximal rating of perceived musculoskeletal effort by the players.

BODY DISCOMFORT

Perceived discomfort was observed to increase as a function of time within both conditions; this was reflected by increases in both the degree of severity as well as the number of players experiencing discomfort (Figure 21, pg 75). Expectedly, the HVR condition induced elevated perceived discomfort ratings. Interestingly, posterior discomfort was more common with twelve runs an over, with the hamstrings, gluteal muscles and lower back the main source of complaint (Figure 23, pg 76). In addition, the quadriceps were highlighted as the main anterior area of discomfort, however, this was similar for both conditions (Figure 22, pg 74), suggesting that despite changes in intensity, players perceived similar discomfort in the quadriceps. The higher number of ratings associated with the hamstrings was expected, as this muscle complex is relied upon to control movement, deceleration in particular, to a greater degree than the quadriceps musculature during this type of intermittent activity (Greig, 2006 and Greig and Siegler, 2009). Further, the muscle recruitment and strength data support the fact that the hamstrings were more affected by the work bouts.

As both work bouts required rapid turning and change of direction, players adopted a stooped posture when crossing the crease which may account for the lower back discomfort, further elevated during the HVC condition when stooped posture was maintained for longer periods. An additional factor that may have influenced the perception of discomfort was the placement of the bat during running, as this is known to influence the sprinting performance of players (Houghton, 2010). As the duration of the work bouts increased, players may have altered the placement of the bat due to discomfort; this in turn may have altered the load placed on the lower back and thus increased the discomfort experienced by the players.

SPRINT PERORMANCE

The ability to generate high speeds quickly and the ability to be agile are essential components of successful batsmen; increases in these, amongst other parameters, improve a player's batting performance (Houghton, 2010). Players participating in the HVR condition were unable or unwilling to maintain sprint times during the seven over protocol. This, in contrast, to the consistent sprint times maintained throughout the MVR condition. Thus doubling the sprint volume had a significant negative impact on sprint performance.

Although an increase in activity duration is known to decrease performance (Morris *et al*., 1998 and Zois *et al*., 2011), this appeared not to be the case in the current study as players were able to maintain sprint times during the MVR condition, the same duration as the more intense condition. Further, performance following an exercise bout known to induce muscle damage (eccentric exercise) has been observed to decrease significantly and may further result in agility performance deficits (Twist and Eston, 2005 and Highton *et al*., 2009). No change in performance was recorded during the MVR condition. On the other hand, the performance decrements recorded during the HVR condition in the current study suggests that the higher sprint frequency was the key determinant of decreased performance likely due to the greater eccentric load (Gabbe *et al*., 2006 ad Highton *et al*., 2009). Furthermore, in this study, rest intervals were less than 90 seconds during the HVR condition and 120 seconds during the MVR condition. Players thus had more recovery time during the more conservative condition. During intermittent sports, it is well known that rest periods are important to allow for recovery (Balsom *et al*., 1992). Sprint performance over a distance of 40m following recovery periods shorter than 90 seconds has been associated with exaggerated decrements (Balsom *et al*., 1992). The decreased performance by players under the HVR condition is therefore likely due to the onset of fatigue, exacerbated by the higher intensity of the HVR condition.

Although the HVR work bout was of a high intensity, Woolmer and Noakes (2008) argue that this is quite representative of real time batting, particularly during the final stages of an innings. Further, players are highly likely to run more frequently during periods of more intense batting requirements. Another possible reason for the performance decrements observed within the HVR work bout is therefore conscious down regulation. Players may have reduced exercise intensity to ensure that no damage to the biological systems developed. This would have been further associated with increased subjective perceptions of effort (De Koning *et al*., 2011 and Swart *et al*., 2012). In addition, the incomplete recovery intervals specific to the current work bout may have exacerbated the psychophysiological changes, such as metabolite disturbances impacting on self confidence to complete the task, resulting in a pacing strategy to delay fatigue onset (Billaut *et al*., 2011).

Although non-significant, the final over of both conditions displayed an improvement in sprinting time, suggesting that players had the potential to increase their speed (Figure 24, pg 77). This indicates a possible reserve within the system again suggesting some form of pacing strategy may have been adopted. Unpublished research from our laboratory has further suggested that pacing does occur in intermittent sports (Christie and Armstrong, Unpublished data). The knowledge of the end point, task intensity and task duration may have resulted in conscious and/or subconscious alterations in work-load over both work bouts in order to reduce the risk of premature fatigue, enabling the completion of each condition (Billaut *et al*., 2011). This ‘end-spurt’ may therefore be due to a conscious decision by the players to increase work output due to the knowledge that the end point was very close (De Koning *et al*., 2011). Based on these arguments therefore it appears more likely that, although muscle fatigue may be present, the observed performance decrements under the HVR condition may be due to a combination of muscle fatigue as well as the adoption of a pacing strategy.

CONCLUSION

The high-volume running condition significantly impacted variables within the biophysical, physiological and perceptual domains of players within the current study to a greater degree than that of the moderate-volume running condition. An increase in physiological (heart rate) and perceptual (ratings of perceived exertion) parameters, with an associated reduction in biophysical (activation levels and isokinetic strength) measures, suggest the presence of both physiological and muscular fatigue, induced to a greater degree as a consequence of the high intensity batting work bout. However, despite the presence of these fatigue indicators, players were able to improve performance following the final over of the HVR condition in particular; this suggests the adoption of a pacing strategy and suggests that muscle fatigue did not impact on the performance of the players in the current study. The results of the current investigation therefore suggest a cricket match of a higher intensity has a greater impact on player performance, particularly the ability to maintain performance when running between the wickets, and, further, impacts the development of muscle fatigue in the involved muscles.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

While cricket has previously been regarded as being minimally taxing on both the physiological and musculoskeletal systems, the evolution of the sport has resulted in elevated demands on the players through the introduction of additional forms of the match, a greater number of matches played per season and limited recovery periods between those matches (Noakes and Durandt, 2000; Nunes and Coetzee, 2007). Although cricket comprises three domains, these being batting, bowling and fielding, this study focused only on the specific musculoskeletal and perceptual demands placed on batsmen during two different match intensities, due to the widely acknowledged lack of literature available on this particular subject (Bartlett, 2003 and Duffield and Drinkwater, 2008). Furthermore, eccentric muscle actions, as required by batting, are widely associated with muscle damage leading to impaired muscle function, and ultimately elevated injury risk (Friden *et al*., 1991; Byrne and Eston, 2002; Gabbe *et al*., 2006; Highton *et al*., 2009). The primary objective of this study was therefore to determine whether any alterations in muscle activation levels, muscle strength, heart rate and selected perceptual responses resulted as a consequence of a batting specific work bout. Further, it aimed to identify what effect intensity level, represented by sprint volume, had on the selected measures of specialist batsmen.

SUMMARY OF PROCEDURES

Initial time-motion analyses conducted by King (2002) were updated through additional analyses of more recent one-day international data and were used to inform the experimental conditions for the current investigation. Players were required to attend three sessions in total. The purpose of the initial session was to collect specific demographic, anthropometric and physiological data and injury history information from each player, as well as to explain fully all procedures to possible participants prior to experimentation. In addition, this first session allowed for habituation to the treadmill, the isokinetic dynamometer and all other equipment involved in experimentation.

The two additional sessions were conducted six to eight days apart, and involved the experimental procedures. On arrival, players were fitted with a heart rate monitor and watch following which resting heart rate was obtained. The dominant lower limb of the player was cleaned with alcohol swabs and shaved to ensure minimal interference during EMG analyses. Electrodes were then placed over the muscle groups of interest; accurate placement during each session was ensured through specific anatomical measurements. Players were then required to perform a warm-up, including cricket-specific stretching and running at slow speeds on the treadmill. Following this, players then completed the three minute treadmill protocol at speeds of 6, 12, 15 and 21km.h^{-1} respectively which allowed for a baseline measure of EMG activity.

Baseline isokinetic strength data was then recorded on the dominant limb of the player using the CYBEX 6000 isokinetic dynamometer. Three repetitions, randomized in order, were performed at speeds of 60°.s^{-1} and 270°.s^{-1}, with a 30 second rest period between each set. Immediately following this, players were requested to pad up in full batting kit, as in a match scenario, and to then complete either the high- or moderate-volume batting-specific protocol. During both work bouts, heart rate, ‘central’ and ‘local’ ratings of perceived exertion (RPE), as well as ratings of body discomfort were recorded on the completion of each over. Following the work bout, players were required to repeat the three minute treadmill protocol as well as the isokinetic strength protocol in order to complete the experimentation.

The following were the dependent variables of interest for the study:

Biophysical variables:	Muscle activity and strength
Physiological variables:	Heart rate

Perceptual variables: ‘Central’ and ‘Local’ RPE and body discomfort

Performance variables: Sprint times

SUMMARY OF RESULTS

Mean anticipatory heart rate responses were the same irrespective of the protocol. Significant ($p<0.05$) increases in heart rate were observed in the transition from rest to exercise, as was expected. Significantly ($p<0.05$) greater heart rates were evident at each time interval when comparing the HVR to the MVR condition.

Significant ($p<0.05$) changes in vastus lateralis (VL) and semitendinosus (ST) activity were observed when comparing conditions. Greater VL activation was observed following HVR at faster speeds and ST following MVR at all speeds. In addition, significant ($p<0.05$) reductions in the biceps femoris (BF) and ST activation were identified over time within selected speeds following HVR, however, BF activation decreased at all speeds following MVR. Furthermore, an increase in the root mean square (RMS) as running speed increased was identified within all muscles under investigation.

Selected concentric and eccentric knee extensors were observed to be vulnerable to change in condition intensity. Reductions observed at $60°.s^{-1}$ as a consequence of the HVR condition were observed in concentric and eccentric peak torque, as well as eccentric total work, whereas the only decrement highlighted at a speed of $270°.s^{-1}$ referred to eccentric average power values. The MVR work bout further induced decrements in concentric and eccentric peak torque, as well as concentric average power values at $60°.s^{-1}$. In addition, knee flexors observed significant ($p<0.05$) decrements in selective concentric and eccentric values. At $60°.s^{-1}$ peak torque and total work were observed to decrease both concentrically and eccentrically as a consequence of the HVR of twelve runs an over. Furthermore, concentric peak torque was observed to decrease at $270°.s^{-1}$, while total work decreased concentrically at 60°.s^{-1}, these findings being as a consequence of the MVR of six runs an over.

Both ‘central’ and ‘local’ RPE displayed significant increases over time, with the more intense condition of twelve runs an over resulting in greater ’central’ ratings from the second to the final over, and greater ‘local’ ratings at overs 3, 5, 6 and the final over. Overall the HVR responses were greater than the values reported during the MVR at the same respective overs, although these did not reflect maximal effort by the players. There were more areas of body discomfort reported as a consequence of the HVR condition (119 in total). In contrast, only 89 were reported following the MVR work bout. More discomfort was identified posteriorly than in the anterior body regions following HVR, with the most frequently cited area of discomfort being the lower back (6) followed by the hamstrings (5) and quadriceps (5). Overall, the level of perceived discomfort was lower in the MVR work bout that that of the HVR.

The general trend was an increase in sprint times with an increase in protocol duration, particularly from the first to the third, fourth, fifth, sixth and final over during the HVR condition. In contrast, there was no change in sprint time when six runs per over were sprinted under the MVR condition. Although this performance decrement indicates possible fatigue, the slight improvement in srint times following the final over, particularly during the HVR condition suggests a pacing strategy may have been adopted by the players.

STATISTICAL HYPOTHESES

MUSCULOSKELETAL HYPOTHESES

With respect to Hypothesis 1a regarding differences in muscle activity between conditions, the results force the null hypothesis to be rejected as VL and ST activation levels were significantly ($p<0.05$) different to that of the alternate condition. In contrast however the null hypothesis is tentatively retained for VM and BF muscles as there was no difference between conditions.

With respect to Hypothesis 1b, the results force the rejection of the null hypothesis, as significant ($p<0.05$) changes were observed within the hamstring musculature as a consequence of the experimental conditions. However, it is tentatively retained with regards to the quadriceps musculature, as no change was observed following either work bout.

With respect to Hypothesis 2a:

(i) The results force the rejection of the null hypothesis as all flexor and extensor values documented significant ($p<0.05$) differences either between conditions or over time.

(ii) The results force the acceptance of the null hypothesis, as no concentric values were significantly ($p<0.05$) influenced by either condition over time.

(iii) The results force the acceptance of the null hypothesis, with the exception of the concentric extensors, as these values significantly ($p<0.05$) altered as a consequence of the MVR condition.

With respect to Hypothesis 2b:

(i) The results force the rejection of the null hypothesis, as both flexor and extensor values displayed significant ($p<0.05$) differences either between conditions or over time within each condition.

(ii) The results force the rejection of the null hypothesis, as both the flexor and extensor values were significantly ($p<0.05$) altered in response to HVR.

(iii) The results force the acceptance of the null hypothesis, as no changes were observed in eccentric average power at $60°.s^{-1}$.

With respect to Hypothesis 2c:

(i) The results force the rejection of the null hypothesis with regards to flexor peak torque, as significant ($p<0.05$) differences were observed between conditions. It is however tentatively retained, as no change was observed in the concentric extensor values.

(ii) The results force the acceptance of the null hypothesis, as no change was observed either between conditions or over time.

(iii) The null hypothesis is accepted with regards to flexor and extensor concentric average power, as no change was identified over time or between conditions.

With respect to Hypothesis 2d:

(i) The null hypothesis was accepted regarding extensor values, as these were observed to change as a consequence of HVR. However, as no difference was observed following conditions or between HVR and MVR, the hypothesis was tentatively retained with respect to eccentric flexor peak torque,

(ii) The results force the acceptance of the null hypothesis, as no change was observed over time or between conditions in either flexor or extensor eccentric values.

(iii) As no change was observed in flexor or extensor eccentric average power, the null hypothesis is accepted.

PHYSIOLOGICAL HYPOTHESIS

With respect to Hypothesis 3, the documented differences between conditions, as well as the significant ($p<0.05$) changes observed over time result in the rejection of the null hypothesis.

PERCEPTUAL HYPOTHESIS

With respect to Hypothesis 4, significant ($p<0.05$) increases were observed in both 'central' and 'local' ratings of perceived effort over time, as well as between conditions. These results therefore force the rejection of the null hypothesis.

PERFORMANCE HYPOTHESIS

With respect to Hypothesis 5, the null hypothesis is rejected as both differences between conditions, as well as changes in sprint performance were identified over time during HVR. However, the null hypothesis is tentatively retained for MVR as no changes were documented with the progression of time.

CONCLUSION

It was clear that the HVR condition significantly increased physiological, perceptual and performance measures to a greater degree than those observed during the MVR condition. The intermittent nature of both conditions was perceived to be more taxing on the cardiovascular rather than the musculoskeletal system, with greater RPE values documented as a consequence of the HVR condition. Muscle recruitment, particularly of the hamstring muscles, decreased significantly over time as a consequence of the more intense condition. The exaggerated isokinetic concentric strength decrement particularly following the HVR condition, in combination with, eccentric strength parameter decrements following both conditions, suggests that greater demands were placed on the hamstring musculature resulting in performance regulation by the players due to the onset of hamstring muscle fatigue. In further support of performance regulation, was the increase in sprint times on completion of the work bouts, particularly following the more intense condition. As this was not as noticeable in the MVR condition, it suggests that the players adopted a strategy in order to cope with the elevated demands of the HVR condition. In addition, a greater awareness of body discomfort was identified throughout the HVR condition, increasing with duration, where the lower back, hamstrings and quadriceps represented the most reported body regions. Of these however, the hamstrings were associated with the highest rating. These results infer a greater degree of musculoskeletal strain and possible injury as a consequence of the higher demands of the HVR protocol.

In order to counteract these increased demands and reduce the risk and prevalence of injury, measures must be taken to improve the eccentric strength of the hamstrings through enhanced eccentric conditioning of the players. This, in combination with increased emphasis on explosive power training would serve to enhance strength, delay the onset of fatigue, avoid the decrements observed in the current study and minimise the risk of injury.

RECOMMENDATIONS

Future batting-specific studies should consider recruiting a larger sample of top-order batsmen in order to increase statistical power of the study. Furthermore, a more homogenous sample of cricket players, with regards to playing level (sub-elite or elite), should be recruited which would further strengthen the validity of the findings. Time-motion analysis data should further be representative of the study sample to which it is applied; in the current study, data from an elite playing level was used to inform the work bouts then performed by sub-elite and university level cricket players.

Both the high- and moderate-volume running conditions required continually high intensity sprinting over a short duration to complete each experimental protocol. Players rarely sprint all out with every ball and thus these conditions are not representative of typical workloads. Future investigations should incorporate various intensities over a longer batting duration, more representative of an *in situ* one-day cricket situation.

The method of muscle activity measurement in the current study is known to be associated with various limitations; more specifically, reduced conductivity with excessive sweating and swelling of the muscle, both of which result with highly eccentric intermittent activities. In order to improve the accuracy of this measure, it is suggested that an alternative method of muscle activity measurement, such as needle EMG, be adopted, the practicality of which is however in question. Alternatively, a neuromuscular performance test should be included in order to improve the information gathered and represent ‘true’ muscle activation.

With regards to isokinetic strength testing, only two speeds were selected in the current study; 60 and 270°.s^{-1}. In order to identify linear changes in strength, it is recommended that an additional intermediate speed of 180°.s^{-1} be incorporated which would allow for the observation of change in strength measures from slower to more functional speeds. Furthermore, a ‘pre’ versus ‘post’ isokinetic fatigue test should be included. This would provide a greater understanding of the time taken for the active muscles to fatigue prior to, and following the protocol in question, providing additional support as to whether muscle fatigue is present as a consequence of the intervention itself. Possible additional functional measures such as the counter-movement jump may be incorporated to provide an alternative method of identifying strength changes.

Not all batting protective gear was worn in this investigation. Future studies may wish to incorporate all additional protective equipment such as a helmet, ball box and chest guards.

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APPENDIX A: GENERAL INFORMATION

ETHICAL APPROVAL

INFORMATION TO THE PLAYER

PLAYER CONSENT FORM

PHYSICAL ACTIVITY SCREENING QUESTIONNAIRE

PAIN PERCEPTION SCALE

PRE-TEST INSTRUCTIONS TO PARTICIPANTS

EQUIPMENT CHECKLIST

ETHICAL APPROVAL

RHODES UNIVERSITY
Grahamstown • 6140 • South Africa

HUMAN KINETICS AND ERGONOMICS ETHICS COMMITTEE REPORT

Student Name: Bronwyn Sheppard

Type of Research: Masters Research Project

Project Title: Musculoskeletal and perceptual responses of batsmen comparing high- and moderate-volume sprints between the wickets

Supervisor: Dr Candice Christie

Report Compiled: 27 May 2011

The requested changes have been made to the satisfaction of all the reviewers. Your application is now approved.

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

Signed

Dr CJ Christie
Chair: Human Kinetics and Ergonomics Ethics Committee

INFORMATION TO THE PLAYER

RHODES UNIVERSITY
Grahamstown • 6140 • South Africa
HUMAN KINETICS AND ERGONOMICS

Cell: 084 500 1134 **Fax**: (046) 603 8934 **E-mail**: g06s4401@campus.ru.ac.za

Dear athlete,

Thank you for expressing an interest in the study entitled:

Musculoskeletal and perceptual responses of batsmen comparing high- and moderate-volumesprints between the wickets.

Through the course of this letter the aim of the study, the specific requirements of the study, and the potential risks and benefits will be explained to you.

This study aims to improve the knowledge about the musculoskeletal and perceptual demands required of cricket batsmen during both a high- and a low-intensity repeated sprint cricket work bout. This improved understanding may allow for enhanced player performance, by identifying muscle fatigue onset and minimising injury risk to players.

You will be required to attend three sessions (one habitation session, and two experimental sessions). During the first session, you will be habituated to the equipment involved in the testing procedure and selective baseline measures will be taken. Furthermore, any questions or concerns may be asked and answered by the researcher at any time.

During session two and three, you will be required to perform the two experimental conditions, and the order of these sessions will be randomised. You will be required to bring, and wear, all cricket kit as in a real match situation. You will perform a warm up and stretch session before commencing either condition. Following this, a baseline muscle activity and strength protocol will be performed before and after both simulated cricket work bouts. The muscle activity protocol involves treadmill running at various speeds (5, 6, 12, 15, 21 $km.h^{-1}$) for a three minute duration, this protocol replicates intermittent activities such as cricket, and allows the muscle activity of four muscles within the quadriceps and hamstring muscle complexes to be measured. Specific muscle strength measures including peak torque, total work and average power of both the quadriceps and hamstring musculature will be obtained using an isokinetic dynamometer (Cybex 6000). You will be required to perform knee extensions at two speeds, 60 $deg.s^{-1}$ and 270 $deg.s^{-1}$, these speeds were selected specifically for muscular strength, and to represent a more functional speed observed when running. The two conditions only differ in terms of the run rate during the cricket work bout: the high-intensity condition requires 12 runs per over, whereas the low-intensity condition requires 6 runs per over.

Risks

As the work bout was developed using data obtained from high scoring one-day cricket matches, the risks are similar to those induced by matches represented by this. However, due to the fact that you will be performing all-out sprints along a wooden walkway, there is a risk of a slip, trip or fall accident, as well as a risk of muscle strain due to these sudden movements. In order to minimise these risks, adequate warm-up and cool-down sessions, administered by the researcher will be undertaken prior to and following each testing session. Furthermore, the wooden walkway on which the sprinting will be performed will be covered in rubber paint in order to increase the friction and reduce this slip, trip or fall risk. The EMG electrodes are pre-filled with a substance that may cause skin irritation, should an irritation identified by the players arise, an alternative piece of equipment that measures the same muscle activity can be used. The isokinetic testing involves maximal muscular exertion from each player, however this machine is designed to resist only as much as the force applied by the player, thus injury risk is minimal. The treadmill protocol poses some risks as you will be required to run at varying speeds (5, 6, 12 ,15, 21 km.h^{-1}) for a total of three minutes, and if you are not familiar with a treadmill there is a risk you will fall off. However, it will be manually operated and if any problems arise, it will be stopped immediately. Instructions on how to use the treadmill correctly will be provided and players will be habituated to running at each speed on the treadmill in order to minimise these risks. In addition to the treadmill habituation, players will also be habituated to all other equipment worn. Heart rate will be monitored continuously during the work bout, and if extreme elevations are observed, testing will be terminated with immediate effect. As this study is voluntary, you can withdraw at any point in the testing process without giving reasons should any discomfort arise from any of the experimental conditions.

Benefits

This study aims to compare the muscle activity and strength changes between a high- and a moderate-volumesprint work bout. Information regarding your maximal concentric and eccentric strength of your lower limb muscles will be provided to you, as well as any strength changes or muscle recruitment patterns observed during the data collection. Furthermore, information related to improving performance and particular changes to training programmes isolating the specific muscles observed in the study will be provided to you. The results can further be used to determine appropriate pacing strategies during one-day cricket, and will optimise the rest breaks during batting. With these results, the coaching staff may implement different training interventions that may improve individual performance, and may reduce the injury risk for all players concerned.

Other

All data collected will be coded and thus your anonymity will be protected. Photographs may also be taken during the sessions for documentation purposes, but these will remain anonymous by blocking out recognisable features, and I will ask permission from you prior to any being taken. If at any stage during the three experimental sessions you wish to withdraw, you may do so without giving reasons and without any consequences. If there are any queries involving the testing procedures, or regarding any feedback, please contact me, my details are provided at the end of this letter.

Thanks for expressing an interest in participating in the study.

Bronwyn Sheppard

HKE

Master's Student

0845001134

g06s4401@campus.ru.ac.za

PLAYER CONSENT FORM

RHODES UNIVERSITY
Grahamstown • 6140 • South Africa
HUMAN KINETICS AND ERGONOMICS

Cell: 084 500 1134 **Fax**: (046) 603 8934 **E-mail**: g06s4401@campus.ru.ac.za

I, ______________________________ having been fully informed of the research entitled:

Musculoskeletal and perceptual responses of batsmen comparing high- and moderate-volumesprints between the wickets.

do hereby give my consent to act as a subject participating in the above mentioned research.

All the procedures have been fully explained to me both verbally and in writing, and the potential risks and benefits have been brought to my attention. By signing this document, I am agreeing to participate in this research, and accept joint responsibility together with the Human Kinetics and Ergonomics Department, in that should an injury occur as a direct result of the protocol being performed during the study, the Human Kinetics and Ergonomics Department will be liable for costs which may ensue and will reimburse the subject to the full amount, i.e. doctors' consultation, medication, rehabilitation etc. The Department will however waive any legal recourse against the researcher and department of Human Kinetics and Ergonomics of Rhodes University, from any and all injuries sustained in the event that the injury is either self-inflicted due to negligence of the subject, or in any way not directly related to the study itself. This waiver shall be binding upon my heirs and personal representatives. I agree to promptly report any signs of discomfort or symptoms of abnormality or distress to the researchers, should any arise. I have been informed on the ability to withdraw my participation from the research at any time. I am aware that my anonymity will be protected at all times, and that all the data collected may be published for scientific purposes.

I have read the information sheet accompanying this form and understand it. Any questions I may have had have been answered by the researcher to my satisfaction.

SUBJECT:

____________________	____________________	____________________
(Print Name)	(Signed)	(Date)

RESEARCHER:

____________________	____________________	____________________
(Print Name)	(Signed)	(Date)

WITNESS:

____________________	____________________	____________________
(Print Name)	(Signed)	(Date)

PHYSICAL ACTIVITY SCREENING QUESTIONNAIRE

Name: _______________

MEDICAL HISTORY

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

- ☐ Heart problems
- ☐ Peripheral vascular disorders
- ☐ High/low blood pressure
- ☐ Epilepsy
- ☐ Other (specify) ____
- ☐ Anemia
- ☐ Asthma
- ☐ Emphysema
- ☐ Migraine
- ☐ Eye Problems
- ☐ Hypoglycemia
- ☐ Diabetes
- ☐ Hyperthyroidism

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

____
____
____

Are you currently suffering from any orthopedic 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 you are currently taking or have taken in the last 6 months.

____
____
____

OTHER HABITS

Please tick the appropriate box.

Do you smoke?

☐ Yes ☐ No

If yes, how many cigarettes per day?

☐ >40 ☐ 20-40 ☐ 10-19 ☐ 1-9

EXERCISE HISTORY

Do you exercise regularly?

☐ Yes ☐ No

How many days per week do you normally spend performing at least 30 minutes of moderate to strenuous exercise?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

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

☐ Yes ☐ No

Can you jog 5km continuously at a moderate pace without discomfort?

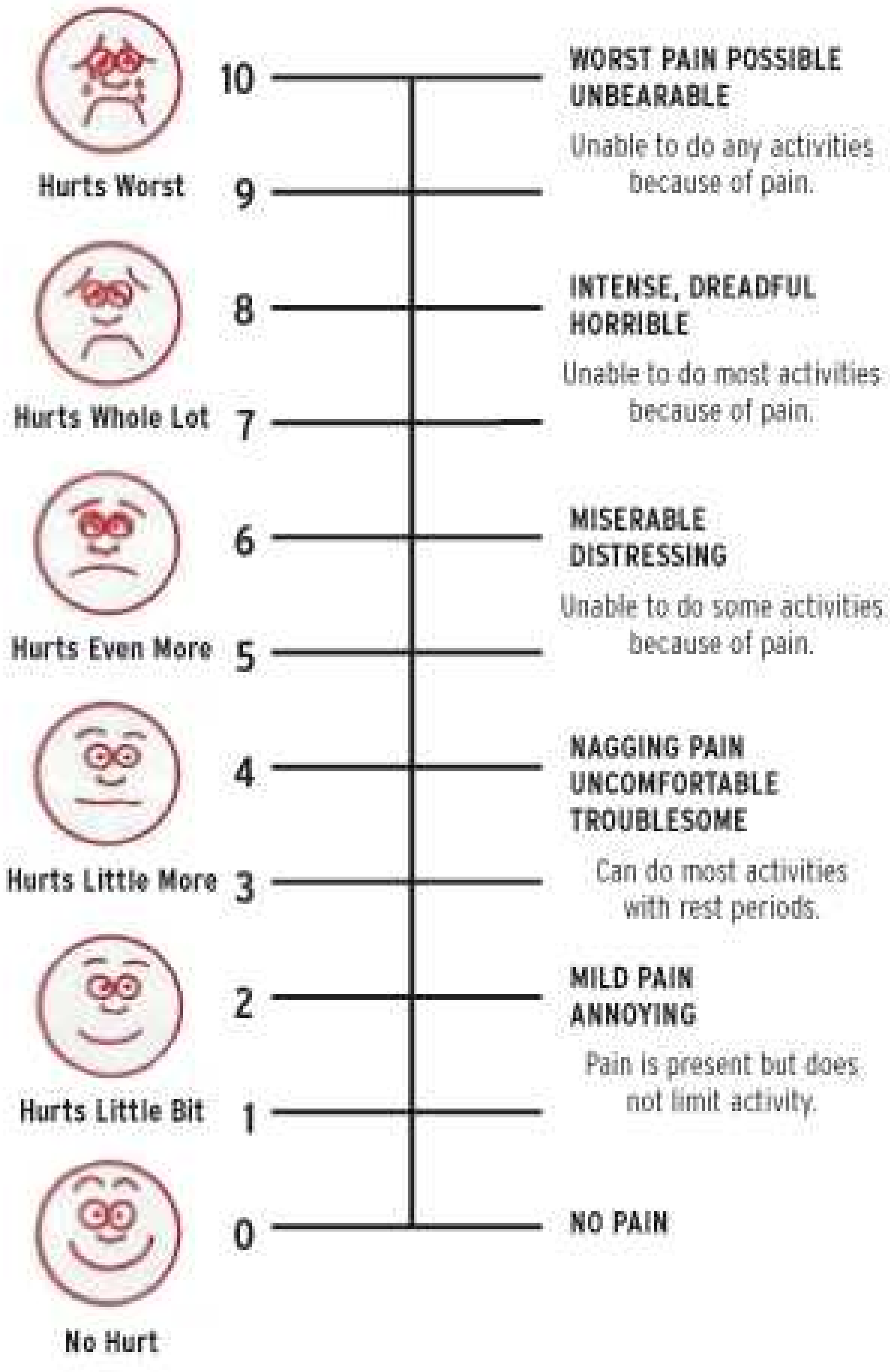
☐ Yes ☐ No

Provide a rough mean of the number of organized/scheduled physical activity sessions you participate in during the week. Tick the appropriate block (s) and fill in the number of sessions.

☐ Jogging ____ ☐ Gym_____ ☐ Touch_____ ☐ Rugby_____

☐ Fitness ____ ☐ Swimming_____ ☐ Other ______

PAIN PERCEPTION SCALE



PRE-TEST INSTRUCTIONS

On arrival to either experimental session, please inform the either the primary researcher or research assistants, if there are any factors known to you that may influence the results, for example, if you are sick and taking prescription medication, are asthmatic, or if you have developed a lower limb injury since the injury history data was recorded. In order for accurate results to be collected, you are asked to follow several instructions prior to experimentation:

24 HOURS BEFORE TESTING:

- Do not participate in strenuous exercise
- Do not consume any alcohol
- Do not take medication unless absolutely necessary, these include; painkillers, cold and flu medications etc.
- Try get a full 8 hours of sleep

ON DAY OF TESTING:

- Try not to eat anything 1 hour 30 minutes before the scheduled start of testing, but make sure a proper meal is eaten before this.

EQUIPMENT CHECKLIST

1. Cybex on and working
2. Datalogger with new batteries, electrodes (five including neutral) and adhesives
3. Tape Measure
4. Razor
5. Alcohol swabs
6. Fiximol adhesive
7. Polar Heart Rate monitor and watch
8. Skinfold Calipers
9. Stopwatch
10. LED System in correct position
11. Treadmill Working
12. Data Sheets (either condition 1 or 2)
13. RPE and body discomfort scales

APPENDIX B: DATA COLLECTION

ORDER OF PROCEDURES

RATING OF PERCEIVED EXERTION SCALE AND EXPLANATION

BODY DISCOMFORT MAP AND SCALE AND EXPLANATION

DATA COLLECTION SHEETS

ORDER OF PROCEDURES

Session I: Introductory and Habituation Session

1. Welcome player

2. Fully explain study

3. Provide letters of information and informed consent

4. Habituate to all equipment

5. Record baseline measures (stature, mass, skinfold measures, reference heart rate and age)

6. Select dates for experimental sessions

Session II and III: Experimentation

1. Welcome player

2. Recap Protocol and ask if player has any illness or injuries since last meeting

3. Attach heart rate monitor and watch and obtain reference measure

4. Prepare dominant limb for electrode attachment

5. Attach electrodes with additional taping, attach cables to data logger and check everything is working

6. Perform warm-up and stretches

7. Perform the pre-protocol EMG protocol

8. Perform the pre-protocol isokinetic strength on the cybex

9. Put cricket kit on

10. Perform cricket work bout (either HVR or MVR condition) recording RPE, heart rate and body discomfort following every over

11. Remove cricket kit
12. Perform post-protocol EMG protocol
13. Perform post-protocol isokinetic strength measures
14. Thank player and remind him of the following testing date

RATING OF PERCEIVED EXERTION SCALE AND EXPLANATION

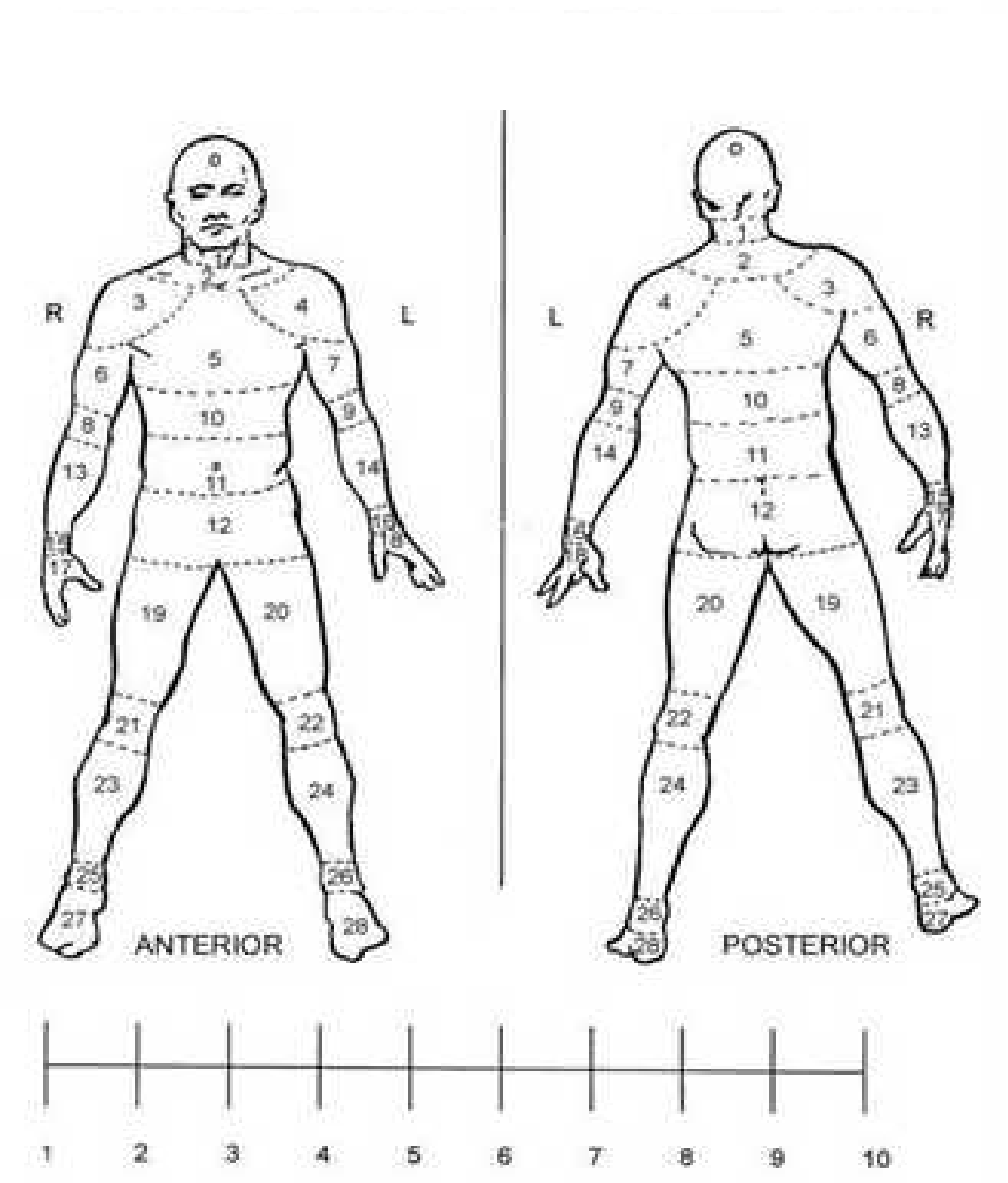
Borg's RPE Scale	
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (Heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

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

EXPLANATION TO PLAYERS

You will be required to perform seven overs with a certain number of sprints each over (depending on the condition), following each over you will be asked to estimate how hard you feel you are working. The first measure will refer to how hard your cardiorespiratory system is working (heart and lungs), and the second will be how hard you perceive your muscles in the lower limbs to be working. A rating of 6 corresponds to your feelings of exertion while standing quietly, whereas a rating of 20 corresponds to maximal exertion.

BODY DISCOMFORT MAP AND SCALE AND EXPLANATION



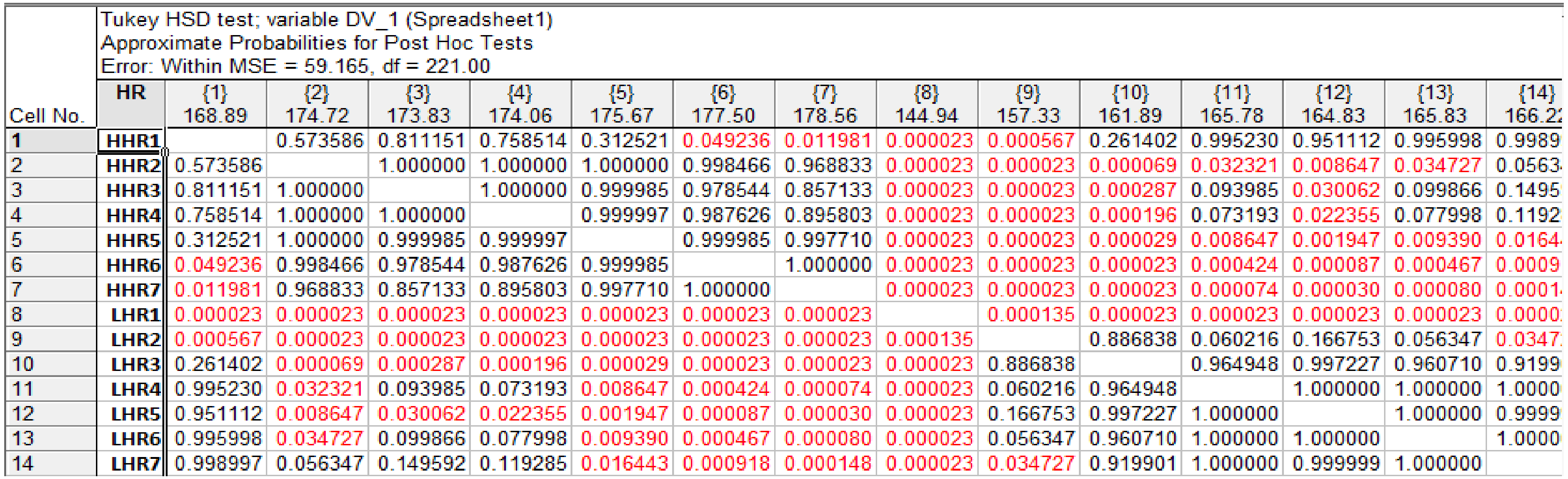
EXPLANATION TO THE PLAYERS

Similarly to RPE, you will be asked to rate your perception of body discomfort following each over of the work bout. You must try determine the exact location of discomfort or pain experienced at that point in time. The map provided will allow you to point to the region and select an intensity between 1 and 10, 1 corresponding to ‘very comfortable’, while 10 corresponds to ‘extreme discomfort’.

APPENDIX C: SUMMARY REPORTS

STATISTICAL ANALYSES

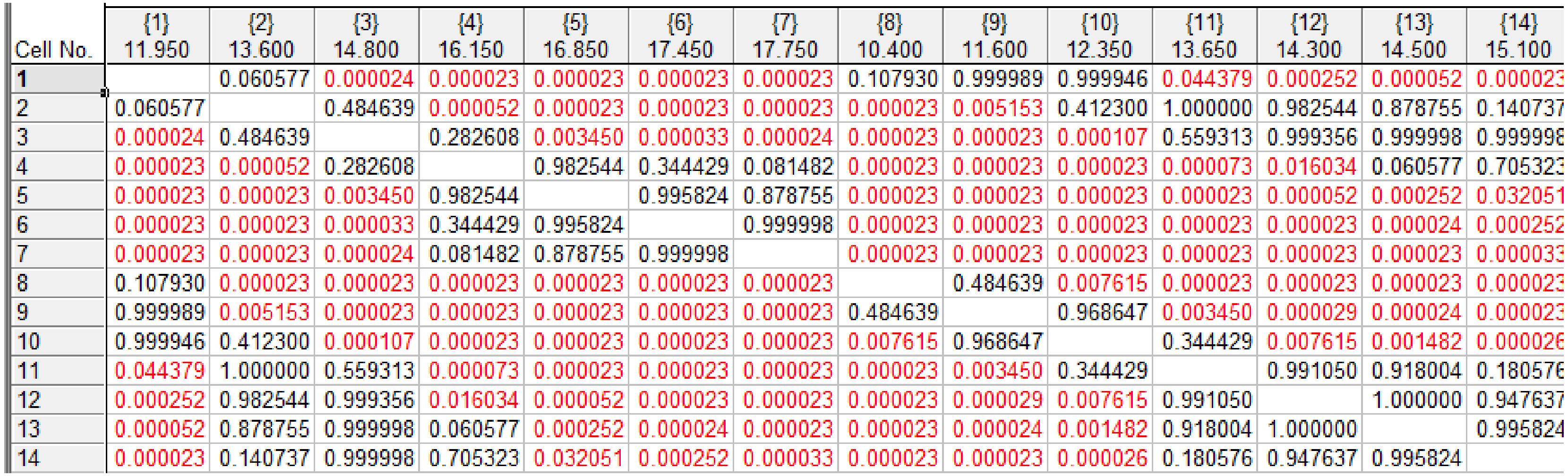
Repeated measures analysis of variance (ANOVA) of the heart rate responses of the players during both protocols over time



Tukey HSD test; variable DV_1 (Spreadsheet1)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 59.165, df = 221.00

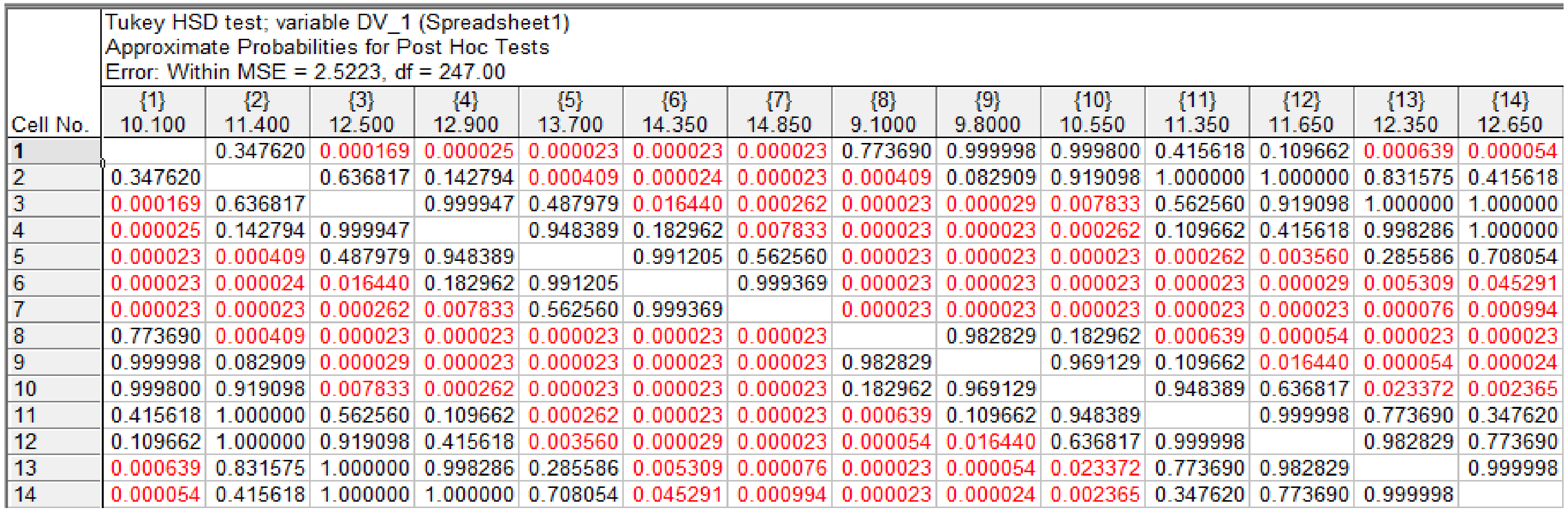
Cell No.	HR	{1} 168.89	{2} 174.72	{3} 173.83	{4} 174.06	{5} 175.67	{6} 177.50	{7} 178.56	{8} 144.94	{9} 157.33	{10} 161.89	{11} 165.78	{12} 164.83	{13} 165.83	{14} 166.2
1	HHR1		0.573586	0.811151	0.758514	0.312521	0.049236	0.011981	0.000023	0.000567	0.261402	0.995230	0.951112	0.995998	0.9989
2	HHR2	0.573586		1.000000	1.000000	1.000000	0.998466	0.968833	0.000023	0.000023	0.000069	0.032321	0.008647	0.034727	0.0563
3	HHR3	0.811151	1.000000		1.000000	0.999985	0.978544	0.857133	0.000023	0.000023	0.000287	0.093985	0.030062	0.099866	0.1495
4	HHR4	0.758514	1.000000	1.000000		0.999997	0.987626	0.895803	0.000023	0.000023	0.000196	0.073193	0.022355	0.077998	0.1192
5	HHR5	0.312521	1.000000	0.999985	0.999997		0.999985	0.997710	0.000023	0.000023	0.000029	0.008647	0.001947	0.009390	0.0164
6	HHR6	0.049236	0.998466	0.978544	0.987626	0.999985		1.000000	0.000023	0.000023	0.000023	0.000424	0.000087	0.000467	0.0009
7	HHR7	0.011981	0.968833	0.857133	0.895803	0.997710	1.000000		0.000023	0.000023	0.000023	0.000074	0.000030	0.000080	0.0001
8	LHR1	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023		0.000135	0.000023	0.000023	0.000023	0.000023	0.0000
9	LHR2	0.000567	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000135		0.886838	0.060216	0.166753	0.056347	0.0347
10	LHR3	0.261402	0.000069	0.000287	0.000196	0.000029	0.000023	0.000023	0.000023	0.886838		0.964948	0.997227	0.960710	0.9199
11	LHR4	0.995230	0.032321	0.093985	0.073193	0.008647	0.000424	0.000074	0.000023	0.060216	0.964948		1.000000	1.000000	1.0000
12	LHR5	0.951112	0.008647	0.030062	0.022355	0.001947	0.000087	0.000030	0.000023	0.166753	0.997227	1.000000		1.000000	0.9999
13	LHR6	0.995998	0.034727	0.099866	0.077998	0.009390	0.000467	0.000080	0.000023	0.056347	0.960710	1.000000	1.000000		1.0000
14	LHR7	0.998997	0.056347	0.149592	0.119285	0.016443	0.000918	0.000148	0.000023	0.034727	0.919901	1.000000	0.999999	1.000000	

Repeated measures ANOVA of the ‘central’ RPE responses of the players during both protocols over time



Cell No.	{1} 11.950	{2} 13.600	{3} 14.800	{4} 16.150	{5} 16.850	{6} 17.450	{7} 17.750	{8} 10.400	{9} 11.600	{10} 12.350	{11} 13.650	{12} 14.300	{13} 14.500	{14} 15.100
1		0.060577	0.000024	0.000023	0.000023	0.000023	0.000023	0.107930	0.999989	0.999946	0.044379	0.000252	0.000052	0.000023
2	0.060577		0.484639	0.000052	0.000023	0.000023	0.000023	0.000023	0.005153	0.412300	1.000000	0.982544	0.878755	0.140737
3	0.000024	0.484639		0.282608	0.003450	0.000033	0.000024	0.000023	0.000023	0.000107	0.559313	0.999356	0.999998	0.999998
4	0.000023	0.000052	0.282608		0.982544	0.344429	0.081482	0.000023	0.000023	0.000023	0.000073	0.016034	0.060577	0.705323
5	0.000023	0.000023	0.003450	0.982544		0.995824	0.878755	0.000023	0.000023	0.000023	0.000023	0.000052	0.000252	0.032051
6	0.000023	0.000023	0.000033	0.344429	0.995824		0.999998	0.000023	0.000023	0.000023	0.000023	0.000023	0.000024	0.000252
7	0.000023	0.000023	0.000024	0.081482	0.878755	0.999998		0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000033
8	0.107930	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023		0.484639	0.007615	0.000023	0.000023	0.000023	0.000023
9	0.999989	0.005153	0.000023	0.000023	0.000023	0.000023	0.000023	0.484639		0.968647	0.003450	0.000029	0.000024	0.000023
10	0.999946	0.412300	0.000107	0.000023	0.000023	0.000023	0.000023	0.007615	0.968647		0.344429	0.007615	0.001482	0.000026
11	0.044379	1.000000	0.559313	0.000073	0.000023	0.000023	0.000023	0.000023	0.003450	0.344429		0.991050	0.918004	0.180576
12	0.000252	0.982544	0.999356	0.016034	0.000052	0.000023	0.000023	0.000023	0.000029	0.007615	0.991050		1.000000	0.947637
13	0.000052	0.878755	0.999998	0.060577	0.000252	0.000024	0.000023	0.000023	0.000024	0.001482	0.918004	1.000000		0.995824
14	0.000023	0.140737	0.999998	0.705323	0.032051	0.000252	0.000033	0.000023	0.000023	0.000026	0.180576	0.947637	0.995824	

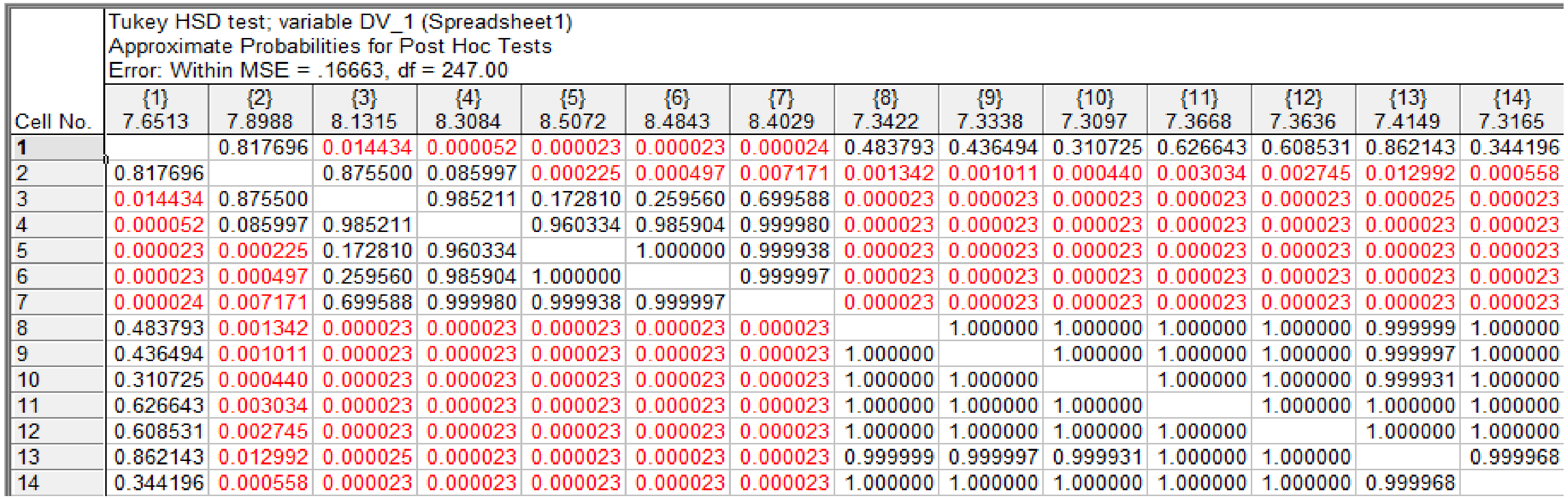
Repeated measures ANOVA of the ‘local’ RPE responses of the players during both protocols over time



Tukey HSD test; variable DV_1 (Spreadsheet1)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 2.5223, df = 247.00

Cell No.	{1} 10.100	{2} 11.400	{3} 12.500	{4} 12.900	{5} 13.700	{6} 14.350	{7} 14.850	{8} 9.1000	{9} 9.8000	{10} 10.550	{11} 11.350	{12} 11.650	{13} 12.350	{14} 12.650
1		0.347620	0.000169	0.000025	0.000023	0.000023	0.000023	0.773690	0.999998	0.999800	0.415618	0.109662	0.000639	0.000054
2	0.347620		0.636817	0.142794	0.000409	0.000024	0.000023	0.000409	0.082909	0.919098	1.000000	1.000000	0.831575	0.415618
3	0.000169	0.636817		0.999947	0.487979	0.016440	0.000262	0.000023	0.000029	0.007833	0.562560	0.919098	1.000000	1.000000
4	0.000025	0.142794	0.999947		0.948389	0.182962	0.007833	0.000023	0.000023	0.000262	0.109662	0.415618	0.998286	1.000000
5	0.000023	0.000409	0.487979	0.948389		0.991205	0.562560	0.000023	0.000023	0.000023	0.000262	0.003560	0.285586	0.708054
6	0.000023	0.000024	0.016440	0.182962	0.991205		0.999369	0.000023	0.000023	0.000023	0.000023	0.000029	0.005309	0.045291
7	0.000023	0.000023	0.000262	0.007833	0.562560	0.999369		0.000023	0.000023	0.000023	0.000023	0.000023	0.000076	0.000994
8	0.773690	0.000409	0.000023	0.000023	0.000023	0.000023	0.000023		0.982829	0.182962	0.000639	0.000054	0.000023	0.000023
9	0.999998	0.082909	0.000029	0.000023	0.000023	0.000023	0.000023	0.982829		0.969129	0.109662	0.016440	0.000054	0.000024
10	0.999800	0.919098	0.007833	0.000262	0.000023	0.000023	0.000023	0.182962	0.969129		0.948389	0.636817	0.023372	0.002365
11	0.415618	1.000000	0.562560	0.109662	0.000262	0.000023	0.000023	0.000639	0.109662	0.948389		0.999998	0.773690	0.347620
12	0.109662	1.000000	0.919098	0.415618	0.003560	0.000029	0.000023	0.000054	0.016440	0.636817	0.999998		0.982829	0.773690
13	0.000639	0.831575	1.000000	0.998286	0.285586	0.005309	0.000076	0.000023	0.000054	0.023372	0.773690	0.982829		0.999998
14	0.000054	0.415618	1.000000	1.000000	0.708054	0.045291	0.000994	0.000023	0.000024	0.002365	0.347620	0.773690	0.999998	

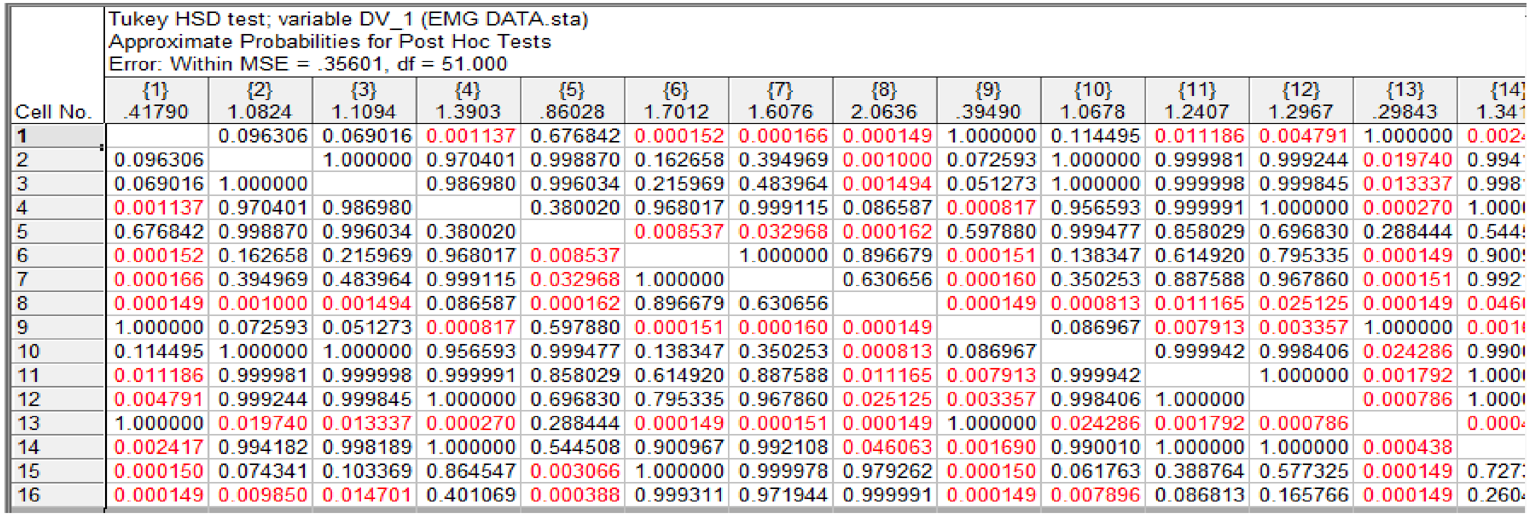
Repeated measures ANOVA of the sprint times of the players during both protocols over time



Tukey HSD test; variable DV_1 (Spreadsheet1)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .16663, df = 247.00

Cell No.	{1} 7.6513	{2} 7.8988	{3} 8.1315	{4} 8.3084	{5} 8.5072	{6} 8.4843	{7} 8.4029	{8} 7.3422	{9} 7.3338	{10} 7.3097	{11} 7.3668	{12} 7.3636	{13} 7.4149	{14} 7.3165
1		0.817696	0.014434	0.000052	0.000023	0.000023	0.000024	0.483793	0.436494	0.310725	0.626643	0.608531	0.862143	0.344196
2	0.817696		0.875500	0.085997	0.000225	0.000497	0.007171	0.001342	0.001011	0.000440	0.003034	0.002745	0.012992	0.000558
3	0.014434	0.875500		0.985211	0.172810	0.259560	0.699588	0.000023	0.000023	0.000023	0.000023	0.000023	0.000025	0.000023
4	0.000052	0.085997	0.985211		0.960334	0.985904	0.999980	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023
5	0.000023	0.000225	0.172810	0.960334		1.000000	0.999938	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023
6	0.000023	0.000497	0.259560	0.985904	1.000000		0.999997	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023
7	0.000024	0.007171	0.699588	0.999980	0.999938	0.999997		0.000023	0.000023	0.000023	0.000023	0.000023	0.000023	0.000023
8	0.483793	0.001342	0.000023	0.000023	0.000023	0.000023	0.000023		1.000000	1.000000	1.000000	1.000000	0.999999	1.000000
9	0.436494	0.001011	0.000023	0.000023	0.000023	0.000023	0.000023	1.000000		1.000000	1.000000	1.000000	0.999997	1.000000
10	0.310725	0.000440	0.000023	0.000023	0.000023	0.000023	0.000023	1.000000	1.000000		1.000000	1.000000	0.999931	1.000000
11	0.626643	0.003034	0.000023	0.000023	0.000023	0.000023	0.000023	1.000000	1.000000	1.000000		1.000000	1.000000	1.000000
12	0.608531	0.002745	0.000023	0.000023	0.000023	0.000023	0.000023	1.000000	1.000000	1.000000	1.000000		1.000000	1.000000
13	0.862143	0.012992	0.000025	0.000023	0.000023	0.000023	0.000023	0.999999	0.999997	0.999931	1.000000	1.000000		0.999968
14	0.344196	0.000558	0.000023	0.000023	0.000023	0.000023	0.000023	1.000000	1.000000	1.000000	1.000000	1.000000	0.999968	

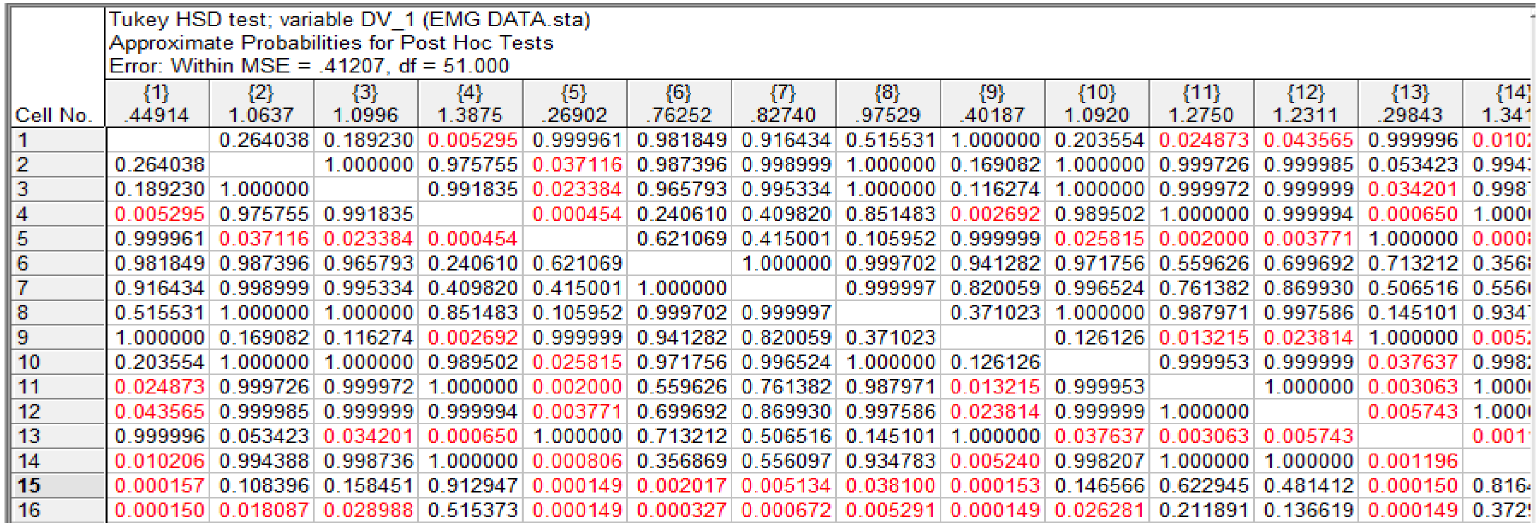
General Linear models (GLM) on the vastus medialis with changes in speed and protocol



Tukey HSD test; variable DV_1 (EMG DATA.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .35601, df = 51.000

Cell No.	{1} .41790	{2} 1.0824	{3} 1.1094	{4} 1.3903	{5} .86028	{6} 1.7012	{7} 1.6076	{8} 2.0636	{9} .39490	{10} 1.0678	{11} 1.2407	{12} 1.2967	{13} .29843	{14} 1.34
1		0.096306	0.069016	0.001137	0.676842	0.000152	0.000166	0.000149	1.000000	0.114495	0.011186	0.004791	1.000000	0.002
2	0.096306		1.000000	0.970401	0.998870	0.162658	0.394969	0.001000	0.072593	1.000000	0.999981	0.999244	0.019740	0.994
3	0.069016	1.000000		0.986980	0.996034	0.215969	0.483964	0.001494	0.051273	1.000000	0.999998	0.999845	0.013337	0.998
4	0.001137	0.970401	0.986980		0.380020	0.968017	0.999115	0.086587	0.000817	0.956593	0.999991	1.000000	0.000270	1.000
5	0.676842	0.998870	0.996034	0.380020		0.008537	0.032968	0.000162	0.597880	0.999477	0.858029	0.696830	0.288444	0.544
6	0.000152	0.162658	0.215969	0.968017	0.008537		1.000000	0.896679	0.000151	0.138347	0.614920	0.795335	0.000149	0.900
7	0.000166	0.394969	0.483964	0.999115	0.032968	1.000000		0.630656	0.000160	0.350253	0.887588	0.967860	0.000151	0.992
8	0.000149	0.001000	0.001494	0.086587	0.000162	0.896679	0.630656		0.000149	0.000813	0.011165	0.025125	0.000149	0.046
9	1.000000	0.072593	0.051273	0.000817	0.597880	0.000151	0.000160	0.000149		0.086967	0.007913	0.003357	1.000000	0.001
10	0.114495	1.000000	1.000000	0.956593	0.999477	0.138347	0.350253	0.000813	0.086967		0.999942	0.998406	0.024286	0.990
11	0.011186	0.999981	0.999998	0.999991	0.858029	0.614920	0.887588	0.011165	0.007913	0.999942		1.000000	0.001792	1.000
12	0.004791	0.999244	0.999845	1.000000	0.696830	0.795335	0.967860	0.025125	0.003357	0.998406	1.000000		0.000786	1.000
13	1.000000	0.019740	0.013337	0.000270	0.288444	0.000149	0.000151	0.000149	1.000000	0.024286	0.001792	0.000786		0.000
14	0.002417	0.994182	0.998189	1.000000	0.544508	0.900967	0.992108	0.046063	0.001690	0.990010	1.000000	1.000000	0.000438	
15	0.000150	0.074341	0.103369	0.864547	0.003066	1.000000	0.999978	0.979262	0.000150	0.061763	0.388764	0.577325	0.000149	0.727
16	0.000149	0.009850	0.014701	0.401069	0.000388	0.999311	0.971944	0.999991	0.000149	0.007896	0.086813	0.165766	0.000149	0.260

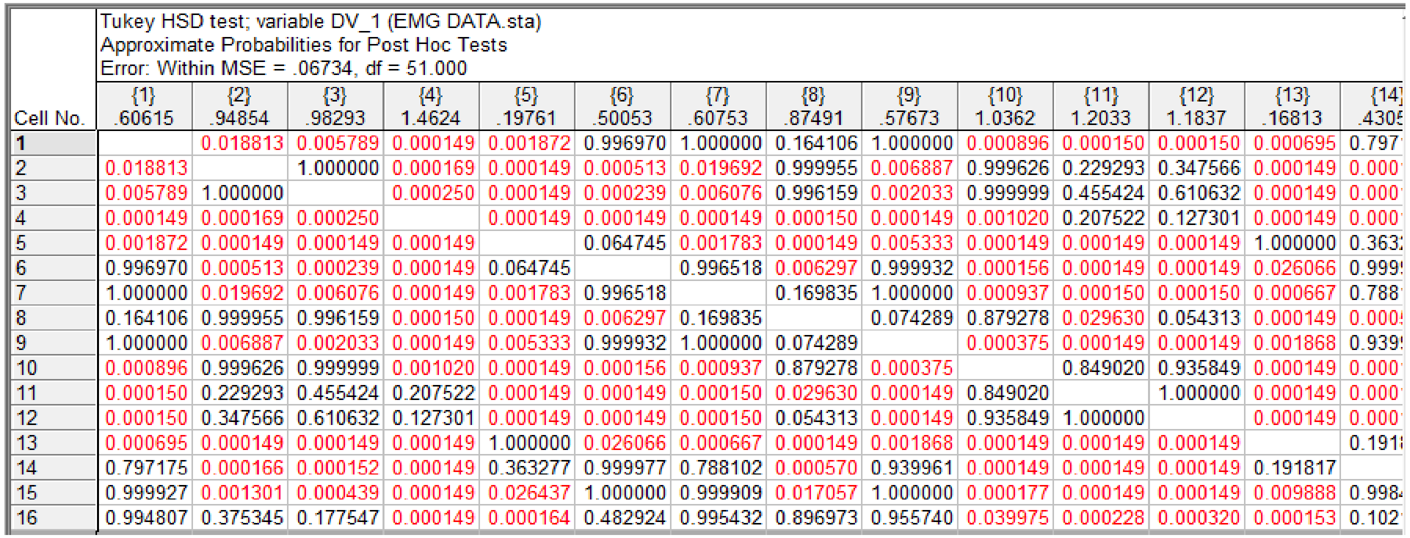
GLM on the vastus lateralis with changes in speed and protocol



Tukey HSD test; variable DV_1 (EMG DATA.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .41207, df = 51.000

Cell No.	{1} .44914	{2} 1.0637	{3} 1.0996	{4} 1.3875	{5} .26902	{6} .76252	{7} .82740	{8} .97529	{9} .40187	{10} 1.0920	{11} 1.2750	{12} 1.2311	{13} .29843	{14} 1.34
1		0.264038	0.189230	0.005295	0.999961	0.981849	0.916434	0.515531	1.000000	0.203554	0.024873	0.043565	0.999996	0.010
2	0.264038		1.000000	0.975755	0.037116	0.987396	0.998999	1.000000	0.169082	1.000000	0.999726	0.999985	0.053423	0.994
3	0.189230	1.000000		0.991835	0.023384	0.965793	0.995334	1.000000	0.116274	1.000000	0.999972	0.999999	0.034201	0.998
4	0.005295	0.975755	0.991835		0.000454	0.240610	0.409820	0.851483	0.002692	0.989502	1.000000	0.999994	0.000650	1.000
5	0.999961	0.037116	0.023384	0.000454		0.621069	0.415001	0.105952	0.999999	0.025815	0.002000	0.003771	1.000000	0.000
6	0.981849	0.987396	0.965793	0.240610	0.621069		1.000000	0.999702	0.941282	0.971756	0.559626	0.699692	0.713212	0.356
7	0.916434	0.998999	0.995334	0.409820	0.415001	1.000000		0.999997	0.820059	0.996524	0.761382	0.869930	0.506516	0.556
8	0.515531	1.000000	1.000000	0.851483	0.105952	0.999702	0.999997		0.371023	1.000000	0.987971	0.997586	0.145101	0.934
9	1.000000	0.169082	0.116274	0.002692	0.999999	0.941282	0.820059	0.371023		0.126126	0.013215	0.023814	1.000000	0.005
10	0.203554	1.000000	1.000000	0.989502	0.025815	0.971756	0.996524	1.000000	0.126126		0.999953	0.999999	0.037637	0.998
11	0.024873	0.999726	0.999972	1.000000	0.002000	0.559626	0.761382	0.987971	0.013215	0.999953		1.000000	0.003063	1.000
12	0.043565	0.999985	0.999999	0.999994	0.003771	0.699692	0.869930	0.997586	0.023814	0.999999	1.000000		0.005743	1.000
13	0.999996	0.053423	0.034201	0.000650	1.000000	0.713212	0.506516	0.145101	1.000000	0.037637	0.003063	0.005743		0.001
14	0.010206	0.994388	0.998736	1.000000	0.000806	0.356869	0.556097	0.934783	0.005240	0.998207	1.000000	1.000000	0.001196	
15	0.000157	0.108396	0.158451	0.912947	0.000149	0.002017	0.005134	0.038100	0.000153	0.146566	0.622945	0.481412	0.000150	0.816
16	0.000150	0.018087	0.028988	0.515373	0.000149	0.000327	0.000672	0.005291	0.000149	0.026281	0.211891	0.136619	0.000149	0.372

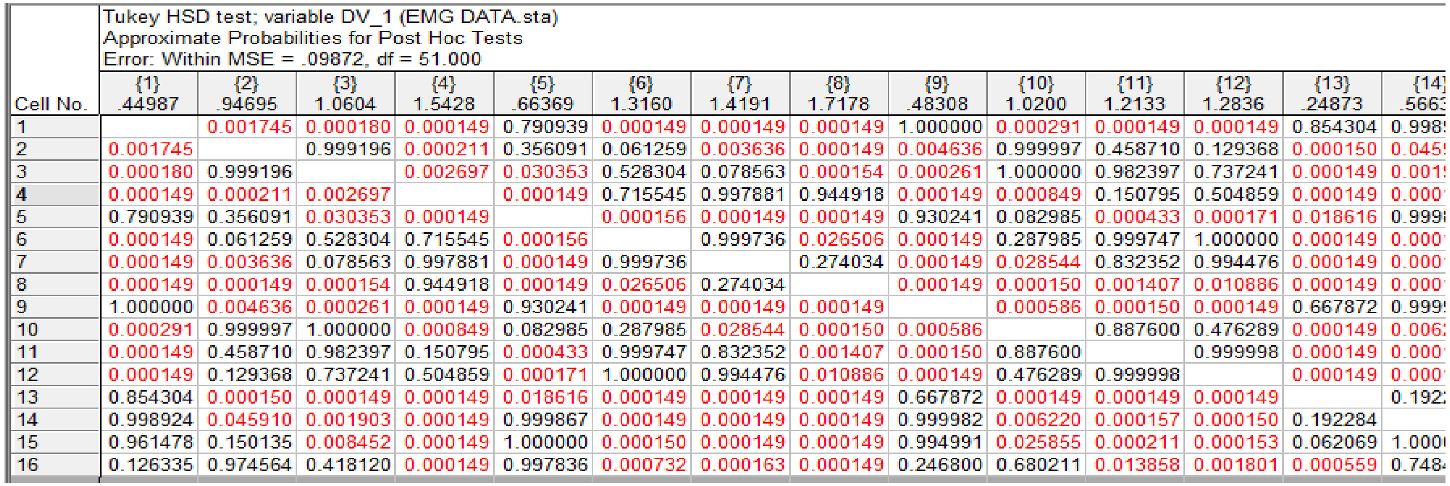
GLM on the biceps femoris with changes in speed and protocol



Tukey HSD test; variable DV_1 (EMG DATA.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .06734, df = 51.000

Cell No.	{1} .60615	{2} .94854	{3} .98293	{4} 1.4624	{5} .19761	{6} .50053	{7} .60753	{8} .87491	{9} .57673	{10} 1.0362	{11} 1.2033	{12} 1.1837	{13} .16813	{14 .430
1		0.018813	0.005789	0.000149	0.001872	0.996970	1.000000	0.164106	1.000000	0.000896	0.000150	0.000150	0.000695	0.797
2	0.018813		1.000000	0.000169	0.000149	0.000513	0.019692	0.999955	0.006887	0.999626	0.229293	0.347566	0.000149	0.000
3	0.005789	1.000000		0.000250	0.000149	0.000239	0.006076	0.996159	0.002033	0.999999	0.455424	0.610632	0.000149	0.000
4	0.000149	0.000169	0.000250		0.000149	0.000149	0.000149	0.000150	0.000149	0.001020	0.207522	0.127301	0.000149	0.000
5	0.001872	0.000149	0.000149	0.000149		0.064745	0.001783	0.000149	0.005333	0.000149	0.000149	0.000149	1.000000	0.363
6	0.996970	0.000513	0.000239	0.000149	0.064745		0.996518	0.006297	0.999932	0.000156	0.000149	0.000149	0.026066	0.999
7	1.000000	0.019692	0.006076	0.000149	0.001783	0.996518		0.169835	1.000000	0.000937	0.000150	0.000150	0.000667	0.788
8	0.164106	0.999955	0.996159	0.000150	0.000149	0.006297	0.169835		0.074289	0.879278	0.029630	0.054313	0.000149	0.000
9	1.000000	0.006887	0.002033	0.000149	0.005333	0.999932	1.000000	0.074289		0.000375	0.000149	0.000149	0.001868	0.939
10	0.000896	0.999626	0.999999	0.001020	0.000149	0.000156	0.000937	0.879278	0.000375		0.849020	0.935849	0.000149	0.000
11	0.000150	0.229293	0.455424	0.207522	0.000149	0.000149	0.000150	0.029630	0.000149	0.849020		1.000000	0.000149	0.000
12	0.000150	0.347566	0.610632	0.127301	0.000149	0.000149	0.000150	0.054313	0.000149	0.935849	1.000000		0.000149	0.000
13	0.000695	0.000149	0.000149	0.000149	1.000000	0.026066	0.000667	0.000149	0.001868	0.000149	0.000149	0.000149		0.191
14	0.797175	0.000166	0.000152	0.000149	0.363277	0.999977	0.788102	0.000570	0.939961	0.000149	0.000149	0.000149	0.191817	
15	0.999927	0.001301	0.000439	0.000149	0.026437	1.000000	0.999909	0.017057	1.000000	0.000177	0.000149	0.000149	0.009888	0.998
16	0.994807	0.375345	0.177547	0.000149	0.000164	0.482924	0.995432	0.896973	0.955740	0.039975	0.000228	0.000320	0.000153	0.102

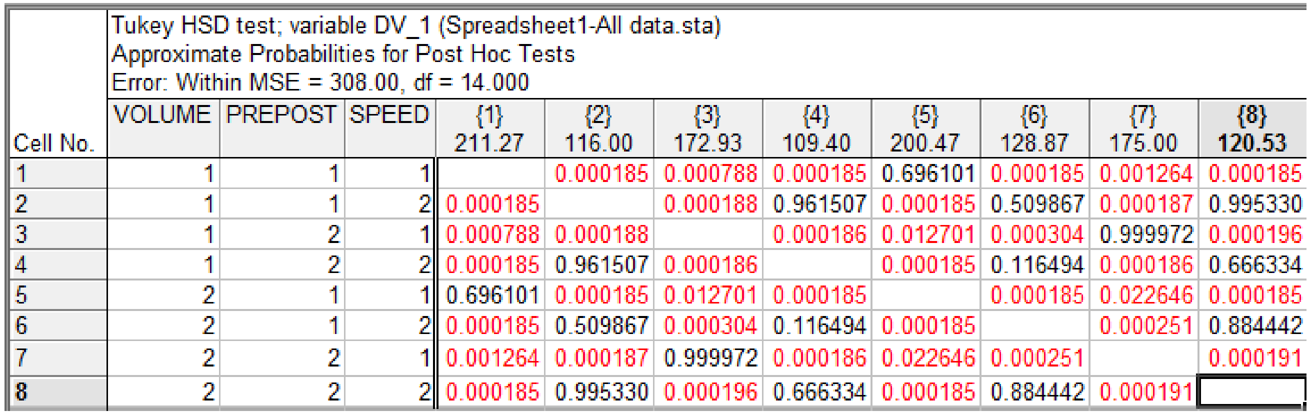
GLM on the semitendinosus with changes in speed and protocol



Tukey HSD test; variable DV_1 (EMG DATA.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .09872, df = 51.000

Cell No.	{1} .44987	{2} .94695	{3} 1.0604	{4} 1.5428	{5} .66369	{6} 1.3160	{7} 1.4191	{8} 1.7178	{9} .48308	{10} 1.0200	{11} 1.2133	{12} 1.2836	{13} .24873	{14 .566
1		0.001745	0.000180	0.000149	0.790939	0.000149	0.000149	0.000149	1.000000	0.000291	0.000149	0.000149	0.854304	0.998
2	0.001745		0.999196	0.000211	0.356091	0.061259	0.003636	0.000149	0.004636	0.999997	0.458710	0.129368	0.000150	0.045
3	0.000180	0.999196		0.002697	0.030353	0.528304	0.078563	0.000154	0.000261	1.000000	0.982397	0.737241	0.000149	0.001
4	0.000149	0.000211	0.002697		0.000149	0.715545	0.997881	0.944918	0.000149	0.000849	0.150795	0.504859	0.000149	0.000
5	0.790939	0.356091	0.030353	0.000149		0.000156	0.000149	0.000149	0.930241	0.082985	0.000433	0.000171	0.018616	0.999
6	0.000149	0.061259	0.528304	0.715545	0.000156		0.999736	0.026506	0.000149	0.287985	0.999747	1.000000	0.000149	0.000
7	0.000149	0.003636	0.078563	0.997881	0.000149	0.999736		0.274034	0.000149	0.028544	0.832352	0.994476	0.000149	0.000
8	0.000149	0.000149	0.000154	0.944918	0.000149	0.026506	0.274034		0.000149	0.000150	0.001407	0.010886	0.000149	0.000
9	1.000000	0.004636	0.000261	0.000149	0.930241	0.000149	0.000149	0.000149		0.000586	0.000150	0.000149	0.667872	0.999
10	0.000291	0.999997	1.000000	0.000849	0.082985	0.287985	0.028544	0.000150	0.000586		0.887600	0.476289	0.000149	0.006
11	0.000149	0.458710	0.982397	0.150795	0.000433	0.999747	0.832352	0.001407	0.000150	0.887600		0.999998	0.000149	0.000
12	0.000149	0.129368	0.737241	0.504859	0.000171	1.000000	0.994476	0.010886	0.000149	0.476289	0.999998		0.000149	0.000
13	0.854304	0.000150	0.000149	0.000149	0.018616	0.000149	0.000149	0.000149	0.667872	0.000149	0.000149	0.000149		0.192
14	0.998924	0.045910	0.001903	0.000149	0.999867	0.000149	0.000149	0.000149	0.999982	0.006220	0.000157	0.000150	0.192284	
15	0.961478	0.150135	0.008452	0.000149	1.000000	0.000150	0.000149	0.000149	0.994991	0.025855	0.000211	0.000153	0.062069	1.000
16	0.126335	0.974564	0.418120	0.000149	0.997836	0.000732	0.000163	0.000149	0.246800	0.680211	0.013858	0.001801	0.000559	0.748

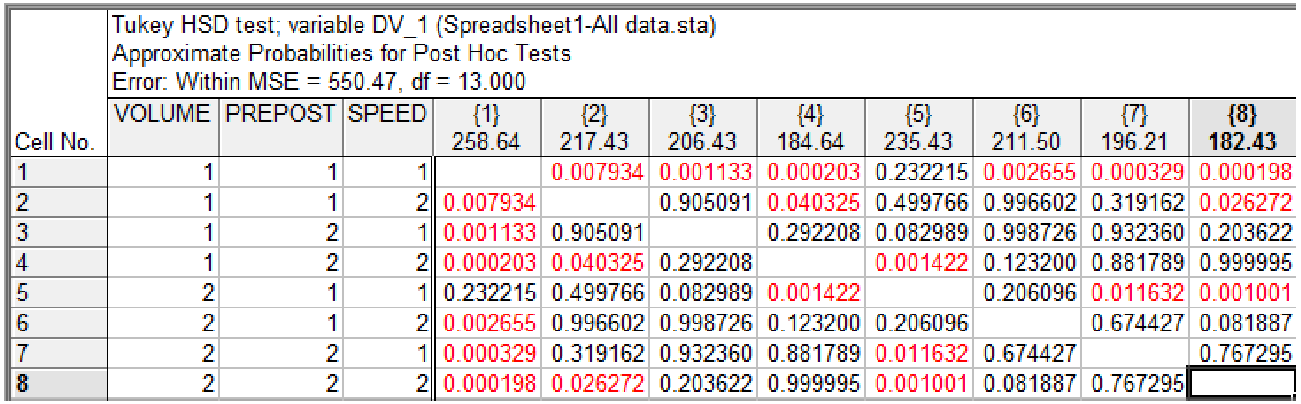
GLM indicating significant differences between concentric extensor peak torque values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 308.00, df = 14.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 211.27	{2} 116.00	{3} 172.93	{4} 109.40	{5} 200.47	{6} 128.87	{7} 175.00	**{8} 120.53**
1	1	1	1		0.000185	0.000788	0.000185	0.696101	0.000185	0.001264	0.000185
2	1	1	2	0.000185		0.000188	0.961507	0.000185	0.509867	0.000187	0.995330
3	1	2	1	0.000788	0.000188		0.000186	0.012701	0.000304	0.999972	0.000196
4	1	2	2	0.000185	0.961507	0.000186		0.000185	0.116494	0.000186	0.666334
5	2	1	1	0.696101	0.000185	0.012701	0.000185		0.000185	0.022646	0.000185
6	2	1	2	0.000185	0.509867	0.000304	0.116494	0.000185		0.000251	0.884442
7	2	2	1	0.001264	0.000187	0.999972	0.000186	0.022646	0.000251		0.000191
8	2	2	2	0.000185	0.995330	0.000196	0.666334	0.000185	0.884442	0.000191	

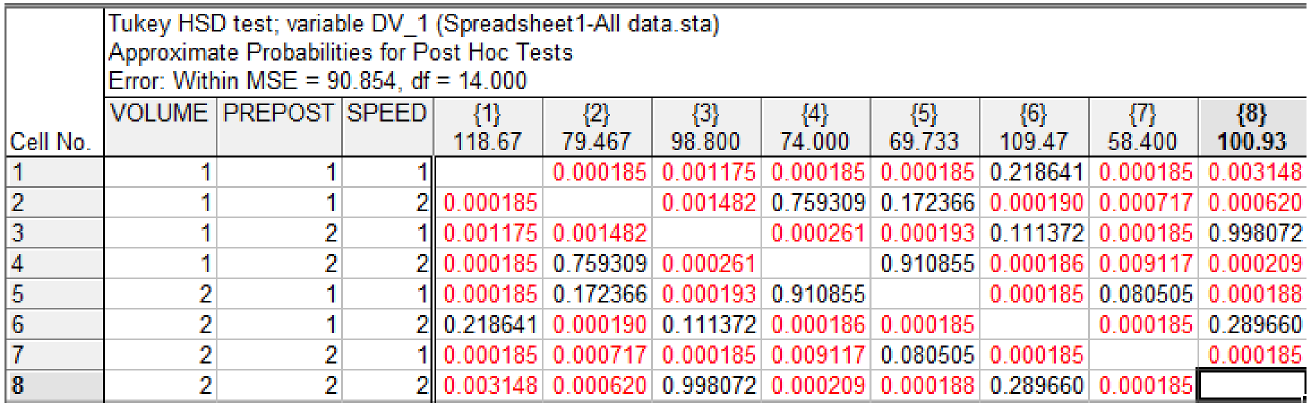
GLM indicating significant differences between eccentric extensor peak torque values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 550.47, df = 13.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 258.64	{2} 217.43	{3} 206.43	{4} 184.64	{5} 235.43	{6} 211.50	{7} 196.21	**{8} 182.43**
1	1	1	1		0.007934	0.001133	0.000203	0.232215	0.002655	0.000329	0.000198
2	1	1	2	0.007934		0.905091	0.040325	0.499766	0.996602	0.319162	0.026272
3	1	2	1	0.001133	0.905091		0.292208	0.082989	0.998726	0.932360	0.203622
4	1	2	2	0.000203	0.040325	0.292208		0.001422	0.123200	0.881789	0.999995
5	2	1	1	0.232215	0.499766	0.082989	0.001422		0.206096	0.011632	0.001001
6	2	1	2	0.002655	0.996602	0.998726	0.123200	0.206096		0.674427	0.081887
7	2	2	1	0.000329	0.319162	0.932360	0.881789	0.011632	0.674427		0.767295
8	2	2	2	0.000198	0.026272	0.203622	0.999995	0.001001	0.081887	0.767295	

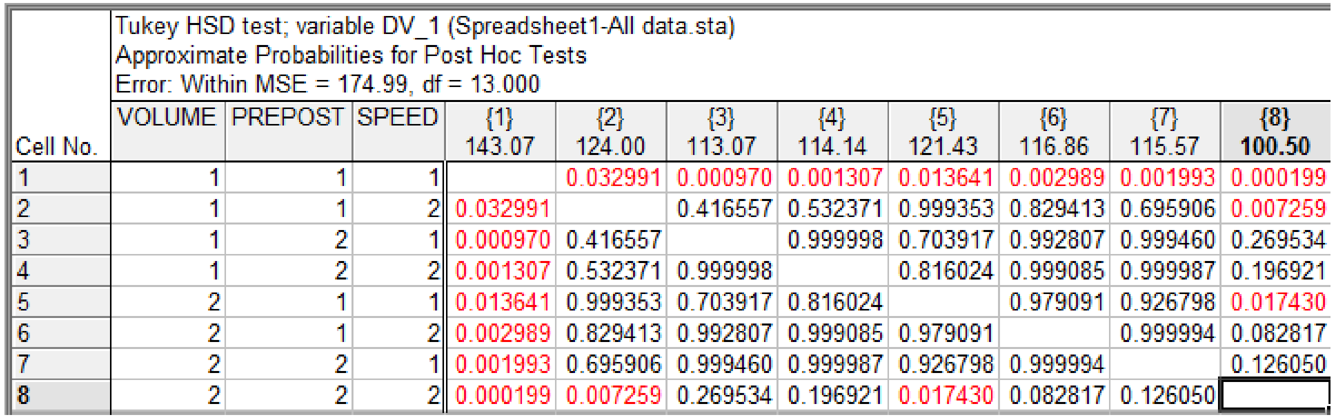
GLM indicating significant differences between concentric flexor peak torque values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 90.854, df = 14.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 118.67	{2} 79.467	{3} 98.800	{4} 74.000	{5} 69.733	{6} 109.47	{7} 58.400	**{8}** **100.93**
1	1	1	1		0.000185	0.001175	0.000185	0.000185	0.218641	0.000185	0.003148
2	1	1	2	0.000185		0.001482	0.759309	0.172366	0.000190	0.000717	0.000620
3	1	2	1	0.001175	0.001482		0.000261	0.000193	0.111372	0.000185	0.998072
4	1	2	2	0.000185	0.759309	0.000261		0.910855	0.000186	0.009117	0.000209
5	2	1	1	0.000185	0.172366	0.000193	0.910855		0.000185	0.080505	0.000188
6	2	1	2	0.218641	0.000190	0.111372	0.000186	0.000185		0.000185	0.289660
7	2	2	1	0.000185	0.000717	0.000185	0.009117	0.080505	0.000185		0.000185
8	2	2	2	0.003148	0.000620	0.998072	0.000209	0.000188	0.289660	0.000185	

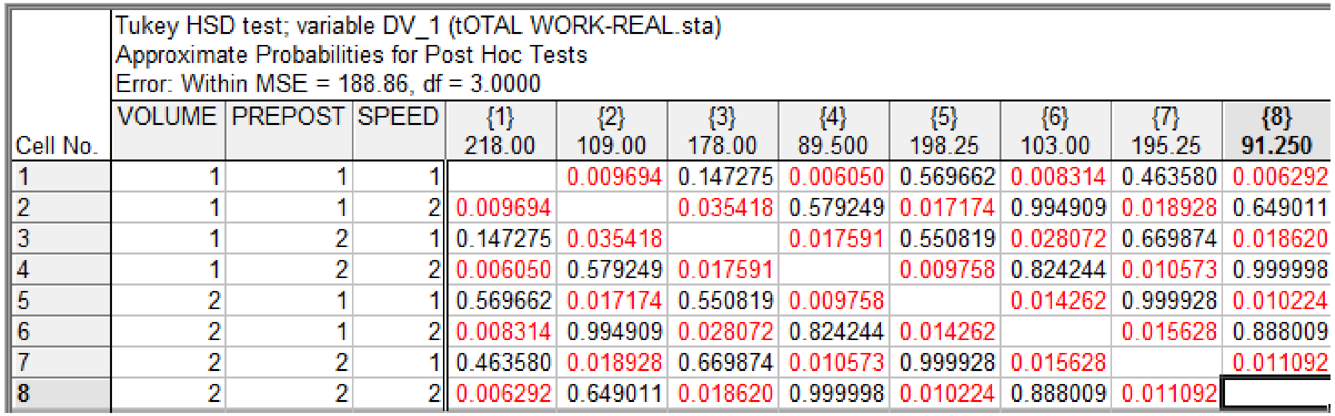
GLM indicating significant differences between eccentric flexor peak torque values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 174.99, df = 13.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 143.07	{2} 124.00	{3} 113.07	{4} 114.14	{5} 121.43	{6} 116.86	{7} 115.57	**{8}** **100.50**
1	1	1	1		0.032991	0.000970	0.001307	0.013641	0.002989	0.001993	0.000199
2	1	1	2	0.032991		0.416557	0.532371	0.999353	0.829413	0.695906	0.007259
3	1	2	1	0.000970	0.416557		0.999998	0.703917	0.992807	0.999460	0.269534
4	1	2	2	0.001307	0.532371	0.999998		0.816024	0.999085	0.999987	0.196921
5	2	1	1	0.013641	0.999353	0.703917	0.816024		0.979091	0.926798	0.017430
6	2	1	2	0.002989	0.829413	0.992807	0.999085	0.979091		0.999994	0.082817
7	2	2	1	0.001993	0.695906	0.999460	0.999987	0.926798	0.999994		0.126050
8	2	2	2	0.000199	0.007259	0.269534	0.196921	0.017430	0.082817	0.126050	

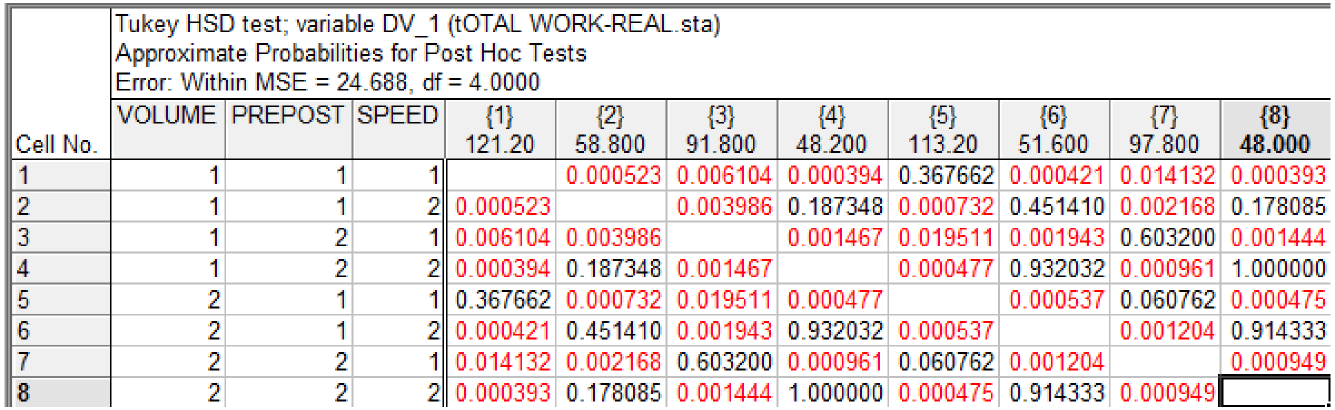
GLM indicating significant differences between concentric extensor total work values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (tOTAL WORK-REAL.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 188.86, df = 3.0000

Cell No.	VOLUME	PREPOST	SPEED	{1} 218.00	{2} 109.00	{3} 178.00	{4} 89.500	{5} 198.25	{6} 103.00	{7} 195.25	**{8} 91.250**
1	1	1	1		0.009694	0.147275	0.006050	0.569662	0.008314	0.463580	0.006292
2	1	1	2	0.009694		0.035418	0.579249	0.017174	0.994909	0.018928	0.649011
3	1	2	1	0.147275	0.035418		0.017591	0.550819	0.028072	0.669874	0.018620
4	1	2	2	0.006050	0.579249	0.017591		0.009758	0.824244	0.010573	0.999998
5	2	1	1	0.569662	0.017174	0.550819	0.009758		0.014262	0.999928	0.010224
6	2	1	2	0.008314	0.994909	0.028072	0.824244	0.014262		0.015628	0.888009
7	2	2	1	0.463580	0.018928	0.669874	0.010573	0.999928	0.015628		0.011092
8	2	2	2	0.006292	0.649011	0.018620	0.999998	0.010224	0.888009	0.011092	

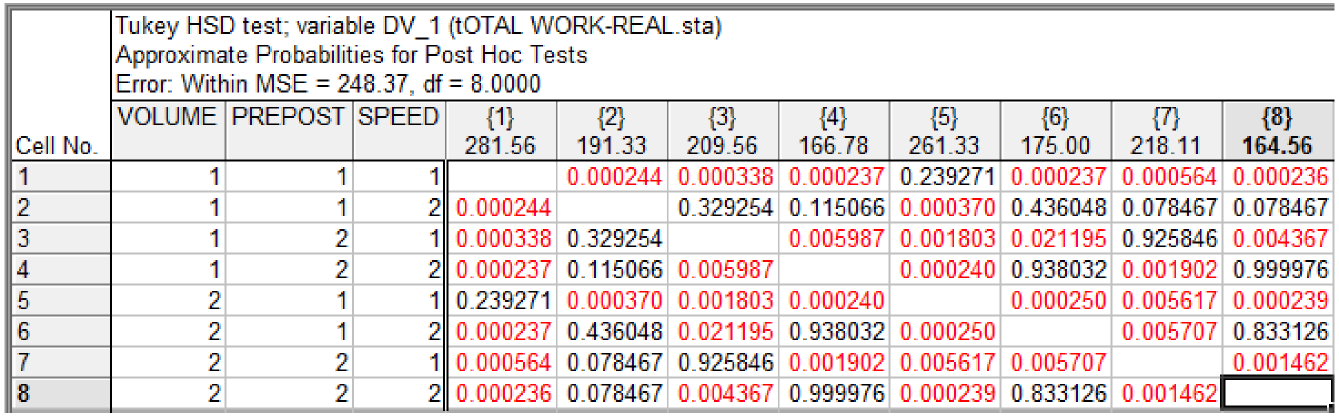
GLM indicating significant differences between eccentric extensor total work values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (tOTAL WORK-REAL.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 24.688, df = 4.0000

Cell No.	VOLUME	PREPOST	SPEED	{1} 121.20	{2} 58.800	{3} 91.800	{4} 48.200	{5} 113.20	{6} 51.600	{7} 97.800	**{8} 48.000**
1	1	1	1		0.000523	0.006104	0.000394	0.367662	0.000421	0.014132	0.000393
2	1	1	2	0.000523		0.003986	0.187348	0.000732	0.451410	0.002168	0.178085
3	1	2	1	0.006104	0.003986		0.001467	0.019511	0.001943	0.603200	0.001444
4	1	2	2	0.000394	0.187348	0.001467		0.000477	0.932032	0.000961	1.000000
5	2	1	1	0.367662	0.000732	0.019511	0.000477		0.000537	0.060762	0.000475
6	2	1	2	0.000421	0.451410	0.001943	0.932032	0.000537		0.001204	0.914333
7	2	2	1	0.014132	0.002168	0.603200	0.000961	0.060762	0.001204		0.000949
8	2	2	2	0.000393	0.178085	0.001444	1.000000	0.000475	0.914333	0.000949	

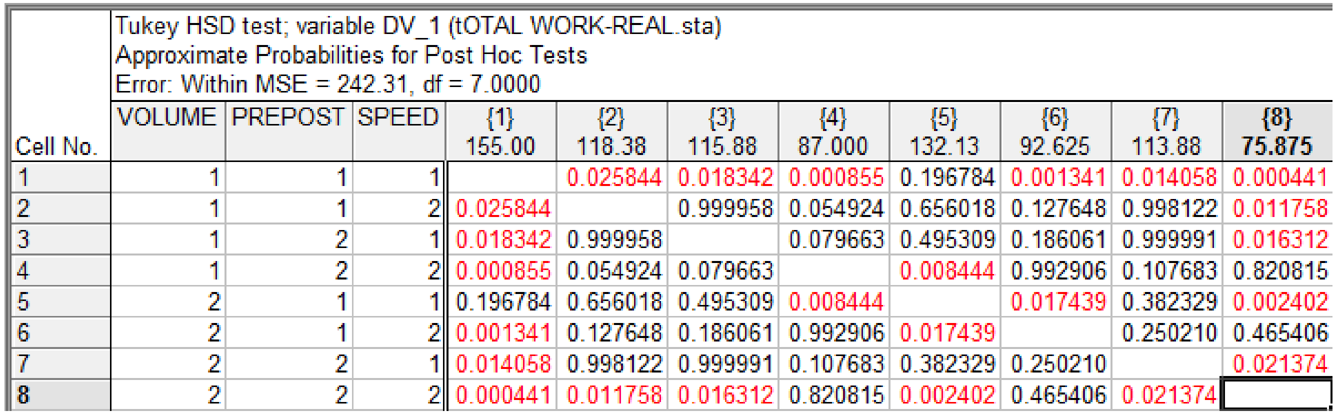
GLM indicating significant differences between concentric flexor total work values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (tOTAL WORK-REAL.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 248.37, df = 8.0000

Cell No.	VOLUME	PREPOST	SPEED	{1} 281.56	{2} 191.33	{3} 209.56	{4} 166.78	{5} 261.33	{6} 175.00	{7} 218.11	**{8} 164.56**
1	1	1	1		0.000244	0.000338	0.000237	0.239271	0.000237	0.000564	0.000236
2	1	1	2	0.000244		0.329254	0.115066	0.000370	0.436048	0.078467	0.078467
3	1	2	1	0.000338	0.329254		0.005987	0.001803	0.021195	0.925846	0.004367
4	1	2	2	0.000237	0.115066	0.005987		0.000240	0.938032	0.001902	0.999976
5	2	1	1	0.239271	0.000370	0.001803	0.000240		0.000250	0.005617	0.000239
6	2	1	2	0.000237	0.436048	0.021195	0.938032	0.000250		0.005707	0.833126
7	2	2	1	0.000564	0.078467	0.925846	0.001902	0.005617	0.005707		0.001462
8	2	2	2	0.000236	0.078467	0.004367	0.999976	0.000239	0.833126	0.001462	

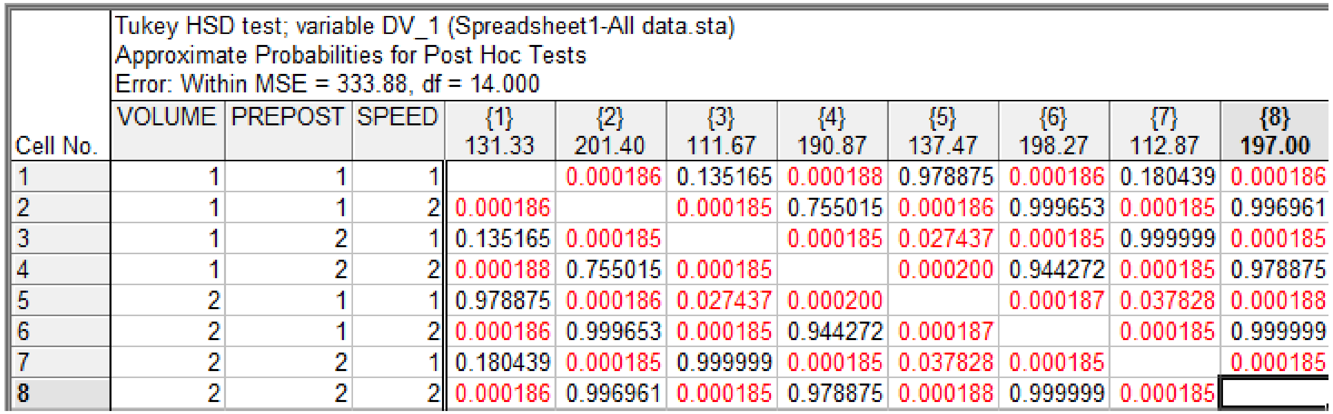
GLM indicating significant differences between eccentric flexor total work values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (tOTAL WORK-REAL.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 242.31, df = 7.0000

Cell No.	VOLUME	PREPOST	SPEED	{1} 155.00	{2} 118.38	{3} 115.88	{4} 87.000	{5} 132.13	{6} 92.625	{7} 113.88	**{8} 75.875**
1	1	1	1		0.025844	0.018342	0.000855	0.196784	0.001341	0.014058	0.000441
2	1	1	2	0.025844		0.999958	0.054924	0.656018	0.127648	0.998122	0.011758
3	1	2	1	0.018342	0.999958		0.079663	0.495309	0.186061	0.999991	0.016312
4	1	2	2	0.000855	0.054924	0.079663		0.008444	0.992906	0.107683	0.820815
5	2	1	1	0.196784	0.656018	0.495309	0.008444		0.017439	0.382329	0.002402
6	2	1	2	0.001341	0.127648	0.186061	0.992906	0.017439		0.250210	0.465406
7	2	2	1	0.014058	0.998122	0.999991	0.107683	0.382329	0.250210		0.021374
8	2	2	2	0.000441	0.011758	0.016312	0.820815	0.002402	0.465406	0.021374	

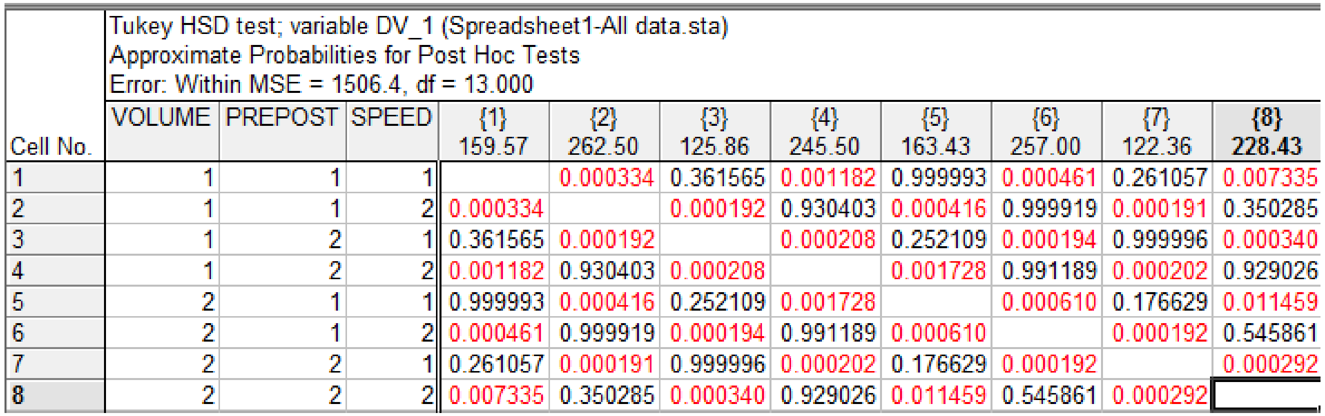
GLM indicating significant differences between concentric extensor average power values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 333.88, df = 14.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 131.33	{2} 201.40	{3} 111.67	{4} 190.87	{5} 137.47	{6} 198.27	{7} 112.87	**{8} 197.00**
1	1	1	1		0.000186	0.135165	0.000188	0.978875	0.000186	0.180439	0.000186
2	1	1	2	0.000186		0.000185	0.755015	0.000186	0.999653	0.000185	0.996961
3	1	2	1	0.135165	0.000185		0.000185	0.027437	0.000185	0.999999	0.000185
4	1	2	2	0.000188	0.755015	0.000185		0.000200	0.944272	0.000185	0.978875
5	2	1	1	0.978875	0.000186	0.027437	0.000200		0.000187	0.037828	0.000188
6	2	1	2	0.000186	0.999653	0.000185	0.944272	0.000187		0.000185	0.999999
7	2	2	1	0.180439	0.000185	0.999999	0.000185	0.037828	0.000185		0.000185
8	2	2	2	0.000186	0.996961	0.000185	0.978875	0.000188	0.999999	0.000185	

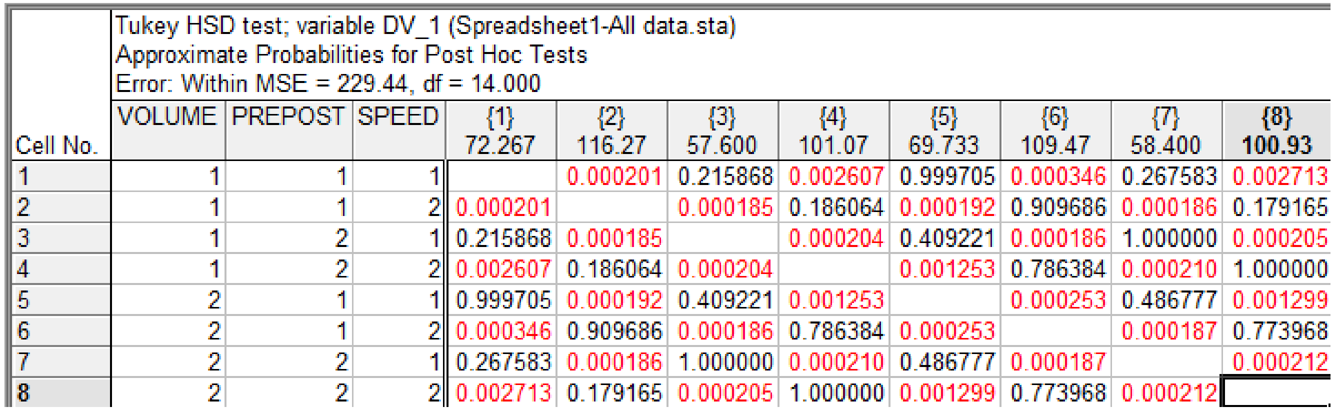
GLM indicating significant differences between eccentric extensor average power values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 1506.4, df = 13.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 159.57	{2} 262.50	{3} 125.86	{4} 245.50	{5} 163.43	{6} 257.00	{7} 122.36	**{8} 228.43**
1	1	1	1		0.000334	0.361565	0.001182	0.999993	0.000461	0.261057	0.007335
2	1	1	2	0.000334		0.000192	0.930403	0.000416	0.999919	0.000191	0.350285
3	1	2	1	0.361565	0.000192		0.000208	0.252109	0.000194	0.999996	0.000340
4	1	2	2	0.001182	0.930403	0.000208		0.001728	0.991189	0.000202	0.929026
5	2	1	1	0.999993	0.000416	0.252109	0.001728		0.000610	0.176629	0.011459
6	2	1	2	0.000461	0.999919	0.000194	0.991189	0.000610		0.000192	0.545861
7	2	2	1	0.261057	0.000191	0.999996	0.000202	0.176629	0.000192		0.000292
8	2	2	2	0.007335	0.350285	0.000340	0.929026	0.011459	0.545861	0.000292	

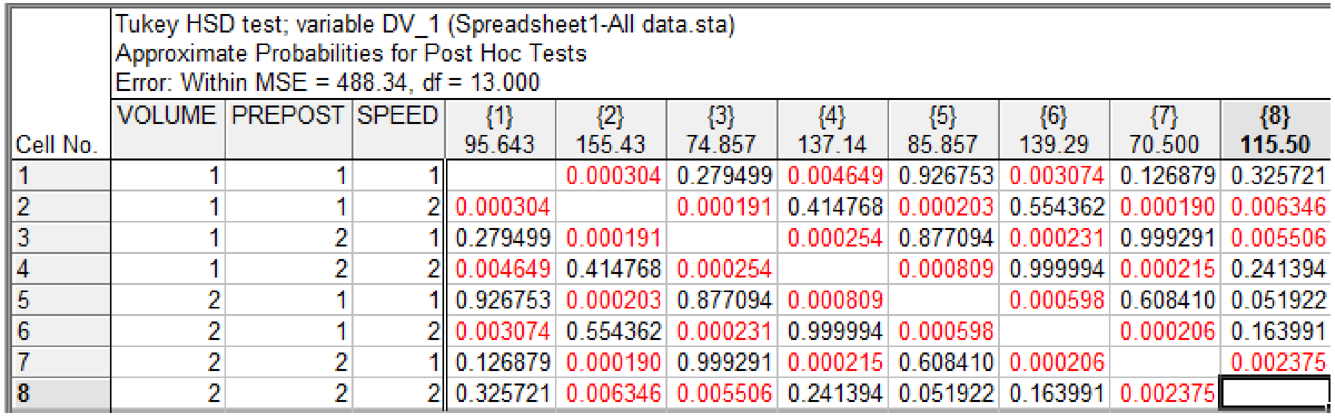
GLM indicating significant differences between concentric flexor average power values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 229.44, df = 14.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 72.267	{2} 116.27	{3} 57.600	{4} 101.07	{5} 69.733	{6} 109.47	{7} 58.400	**{8} 100.93**
1	1	1	1		0.000201	0.215868	0.002607	0.999705	0.000346	0.267583	0.002713
2	1	1	2	0.000201		0.000185	0.186064	0.000192	0.909686	0.000186	0.179165
3	1	2	1	0.215868	0.000185		0.000204	0.409221	0.000186	1.000000	0.000205
4	1	2	2	0.002607	0.186064	0.000204		0.001253	0.786384	0.000210	1.000000
5	2	1	1	0.999705	0.000192	0.409221	0.001253		0.000253	0.486777	0.001299
6	2	1	2	0.000346	0.909686	0.000186	0.786384	0.000253		0.000187	0.773968
7	2	2	1	0.267583	0.000186	1.000000	0.000210	0.486777	0.000187		0.000212
8	2	2	2	0.002713	0.179165	0.000205	1.000000	0.001299	0.773968	0.000212	

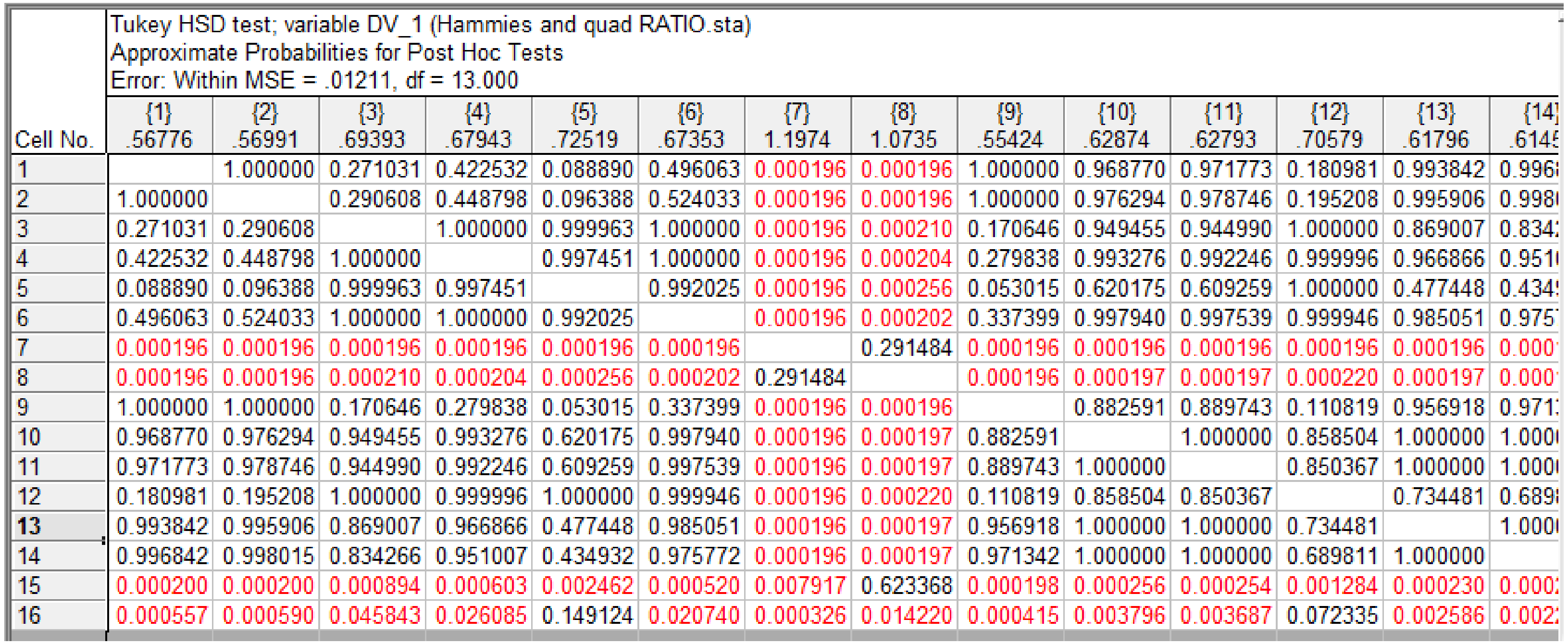
GLM indicating significant differences between eccentric flexor average power values as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Spreadsheet1-All data.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 488.34, df = 13.000

Cell No.	VOLUME	PREPOST	SPEED	{1} 95.643	{2} 155.43	{3} 74.857	{4} 137.14	{5} 85.857	{6} 139.29	{7} 70.500	**{8} 115.50**
1	1	1	1		0.000304	0.279499	0.004649	0.926753	0.003074	0.126879	0.325721
2	1	1	2	0.000304		0.000191	0.414768	0.000203	0.554362	0.000190	0.006346
3	1	2	1	0.279499	0.000191		0.000254	0.877094	0.000231	0.999291	0.005506
4	1	2	2	0.004649	0.414768	0.000254		0.000809	0.999994	0.000215	0.241394
5	2	1	1	0.926753	0.000203	0.877094	0.000809		0.000598	0.608410	0.051922
6	2	1	2	0.003074	0.554362	0.000231	0.999994	0.000598		0.000206	0.163991
7	2	2	1	0.126879	0.000190	0.999291	0.000215	0.608410	0.000206		0.002375
8	2	2	2	0.325721	0.006346	0.005506	0.241394	0.051922	0.163991	0.002375	

GLM indicating significant differences between H:Q ratios as a consequence of speed and the protocol



Tukey HSD test; variable DV_1 (Hammies and quad RATIO.sta)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .01211, df = 13.000

Cell No.	{1} .56776	{2} .56991	{3} .69393	{4} .67943	{5} .72519	{6} .67353	{7} 1.1974	{8} 1.0735	{9} .55424	{10} .62874	{11} .62793	{12} .70579	{13} .61796	{14 .614
1		1.000000	0.271031	0.422532	0.088890	0.496063	0.000196	0.000196	1.000000	0.968770	0.971773	0.180981	0.993842	0.996
2	1.000000		0.290608	0.448798	0.096388	0.524033	0.000196	0.000196	1.000000	0.976294	0.978746	0.195208	0.995906	0.998
3	0.271031	0.290608		1.000000	0.999963	1.000000	0.000196	0.000210	0.170646	0.949455	0.944990	1.000000	0.869007	0.834
4	0.422532	0.448798	1.000000		0.997451	1.000000	0.000196	0.000204	0.279838	0.993276	0.992246	0.999996	0.966866	0.951
5	0.088890	0.096388	0.999963	0.997451		0.992025	0.000196	0.000256	0.053015	0.620175	0.609259	1.000000	0.477448	0.434
6	0.496063	0.524033	1.000000	1.000000	0.992025		0.000196	0.000202	0.337399	0.997940	0.997539	0.999946	0.985051	0.975
7	0.000196	0.000196	0.000196	0.000196	0.000196	0.000196		0.291484	0.000196	0.000196	0.000196	0.000196	0.000196	0.000
8	0.000196	0.000196	0.000210	0.000204	0.000256	0.000202	0.291484		0.000196	0.000197	0.000197	0.000220	0.000197	0.000
9	1.000000	1.000000	0.170646	0.279838	0.053015	0.337399	0.000196	0.000196		0.882591	0.889743	0.110819	0.956918	0.971
10	0.968770	0.976294	0.949455	0.993276	0.620175	0.997940	0.000196	0.000197	0.882591		1.000000	0.858504	1.000000	1.000
11	0.971773	0.978746	0.944990	0.992246	0.609259	0.997539	0.000196	0.000197	0.889743	1.000000		0.850367	1.000000	1.000
12	0.180981	0.195208	1.000000	0.999996	1.000000	0.999946	0.000196	0.000220	0.110819	0.858504	0.850367		0.734481	0.689
13	0.993842	0.995906	0.869007	0.966866	0.477448	0.985051	0.000196	0.000197	0.956918	1.000000	1.000000	0.734481		1.000
14	0.996842	0.998015	0.834266	0.951007	0.434932	0.975772	0.000196	0.000197	0.971342	1.000000	1.000000	0.689811	1.000000	
15	0.000200	0.000200	0.000894	0.000603	0.002462	0.000520	0.007917	0.623368	0.000198	0.000256	0.000254	0.001284	0.000230	0.000
16	0.000557	0.000590	0.045843	0.026085	0.149124	0.020740	0.000326	0.014220	0.000415	0.003796	0.003687	0.072335	0.002586	0.002