CHANGES IN MUSCLE RECRUITMENT, FUNCTIONAL STRENGTH AND RATINGS OF PERCEIVED EFFORT DURING AN 8-OVER BOWLING SPELL: IMPACT ON PERFORMANCE

BY

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MASTERS THESIS PROJECT

Submitted in fulfillment of the requirements for the Degree Bachelor of Science (Masters)

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Rhodes University, 2013

Grahamstown, South Africa

ABSTRACT

Background: The musculoskeletal demands placed on the lower limb musculature of fast bowlers over time have not received much attention. In particular, measures of muscle recruitment changes have, to the author's knowledge, not been considered.

Objective: The present study, therefore sought to establish any associations between an eight over, simulated fast bowling spell, and muscle activation patterns, power output, perceptual demands, and changes in performance. This will enable improvements in the development of training programmes.

Methods: Players' were required to attend two 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. In addition, this first session allowed for habituation with the treadmill, the jump meter and all other equipment involved in experimentation. The second testing session involved electrode attachment sites being identified on player's dominant leg. The areas were then shaved, wiped with an alcohol swab and left to dry, to ensure good connectivity. Pre- and post- measures of muscle activity and functional strength of the lower limbs were recorded in the Department of Human Kinetics and Ergonomics. The protocol took place at the Kingswood High Performance Centre, which is in close proximity to the initial testing site. The protocol involved players bowling eight overs (48 balls). During the protocol, accuracy, ball release speed and perceptual measures were recorded at the end of each over. After the protocol, players were driven back to the Human Kinetics and Ergonomics Department where post-testing measures were completed. The dependable variables of interest were muscle activation, functional strength of the lower limbs, 'local' ratings of perceived exertion (RPE), body discomfort, accuracy, and ball release speed.

Results: For all muscles it was shown that, as the speed increased so did the muscle activity in players' lower limbs. There were no significant changes in muscle activity pre- versus post-protocol. There was however, a general trend of decreasing muscle activity post protocol at higher testing speeds. There were significant ($p<0.05$) decreases in peak power following the simulated eight over bowling spell. 'Local' RPE displayed a significant ($P<0.05$) increase with each additional over and were observed to reach the 'heavy' category. The players' highest discomfort area was in the lower back, with 13 players perceiving discomfort in this region following the eight over spell. The shoulder and chest were another two areas player's indicated discomfort with eight players selecting the dominant shoulder. Seven players complained of the dominant side pectoral muscle, leading foot and dominant latissimus dorsi muscle being uncomfortable. Interestingly, the dominant pectoral showed the highest body discomfort ratings amongst players. There were no significant changes in accuracy between overs although there were large inter-individual differences in accuracy points between players. The decrease in ball release speed observed during over seven was shown to be significantly ($p<0.05$) lower than overs one to four.

Conclusion: The power output and perceived strain results of the players, appears to indicate the presence of fatigue in players. However, the results are not conclusive, as the fatigue was not shown in muscle recruitment patterns, as well as the body discomfort ratings. There was a non-significant trend observed in the lower limb muscle activation decreasing at higher speeds. Players were able to maintain accuracy. However, the significantly lower ball release speed observed during over seven showed players performance decreasing.

ACKNOWLEDGEMENTS

The following people deserve my acknowledgement and sincere gratitude for their utmost support, assistance and guidance throughout the duration of this project:

Most importantly, my supervisor, Candice Christie, for everything she has done for me. Her guidance has helped me grow academically and personally over the last years. Thank you for your patience as well as so many hours of hard work. This thesis would not have been possible without your in-depth knowledge in the field and constant assistance and guidance, and willingness to sit down and discuss problems with a holistic approach.

Bronwyn Sheppard, thank you for helping me and teaching me how to operate and use all the equipment, and for always being there anytime I had any questions. Your help was greatly appreciated. To Lee Pote and Andrea Elliot, my research assistants. A big thank you to Lee Pote, without your help: setting up the protocol, recruiting subjects, and to Andrea for her hours of testing players, it would not have been possible without the two of you.

To all my fast bowlers without whom this study would not have been possible. I thank them for their co-operation, understanding and willingness to sacrifice their personal time to help me achieve this endeavor.

To all the remaining people who made this possible; more specifically, my digs-mates and class, all the support kept me going when I felt overwhelmed. To the HKE department, June and all the lecturers, who offered their assistance when necessary.

A big thank you to Megan Button, Sirion Roberston, Kirsty Barford for reading through each chapter many times over. Proof reading, and correcting any mistakes. Inspiring and motivating me to keep at it, thanks for your help.

To the National Research Foundation. For their financial support throughout the duration of my Master‘s. Thank you for funding this investigation, paying for all the new and updated equipment which made this study possible.

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CHAPTER I

INTRODUCTION

BACKGROUND TO THE STUDY

Cricket is a sport which requires a high level of skill, and cricketers today need to have quick reflexes and be able to maintain patience and concentration for long periods of time (Woolmer *et al.,* 2008). Attributes which are also imperative to the game of cricket are high levels of agility, speed and the ability to accelerate and decelerate rapidly, all of which require optimal levels of fitness (Woolmer *et al.,* 2008). However, due to the lack of research on cricket in general, not much is known about the physical and perceived demands of all forms of the game. Most of the training programmes for cricketers are therefore not scientifically based. Further, most of the research has tended to focus on lower back biomechanics, particularly in fast bowlers (Elliot, 2000; Portus *et al.,* 2000; Foster *et al.,* 2011), and while the importance of understanding this and the link with injury risk is important, it is contended that relatively little attention has been afforded the lower limb musculature, which is also frequently injured.

In studies done in Australia 886 injuries were recorded, of which 92% were first time occurrences (Stretch 2007). The injuries were mainly sustained while bowling (45%), with lower limb injuries accounting for 49% of these. Of these injuries, 72% where a result of muscle/tendon strains (Stretch 2007). In studies done in South Africa, 1606 injuries were recorded; first-time injuries accounted for 65% of total injuries (Stretch and Venter, 2005). Bowling accounted for 40% of the injuries, and the majority of the injuries to fast bowlers occurred in the lower limb, accounting for 55% (Stretch and Venter, 2005). Studies in England reported 990 injuries, with bowlers having the highest injury incidence; 70.1 injuries per 1 000 days (Leary and White, 2000). The majority of injuries occurred to the lower limbs (45%) of bowlers, which is in agreement with all previous literature on injury patterns in cricket (Leary and White, 2000; Orchard *et al*., 2002; Stretch and Venter, 2005). Lower limb injuries in cricket are predominantly hamstring, quadriceps and calf muscle strains (Payne, 1987; Stretch, 1989; Stretch, 2001; Brooks *et al*., 2005) probably due to the all-out sprint efforts and rapid acceleration plus deceleration required in many aspects of the game. With respect to the bowling action, run-ups for fast bowlers vary from player to player although the majority of fast bowlers have a run-up of between 10 m and 30 m. The run-up and delivery requires rapid initiation of forward momentum, high running speeds and then rapid deceleration with the delivery. The total distance covered by fast bowlers during a one day international (ODI), is 13.4 ± 0.7 km (Petersen *et al.,* 2010). Thus the continuous acceleration and deceleration required by fast bowlers demands high levels of eccentric muscle activity in the lower limbs over a considerable distance and period of time. It is well known that single bouts of unaccustomed eccentric muscle action cause skeletal muscle damage (Morgan and Allen, 1999). Eccentric actions are heavily involved in running and more crucially in this study, while sprinting and during the deceleration movement, as they are exerting a braking force to control the motion of the body (Whitehead *et al*., 1998). Further, running requires continuous activation of the hamstring muscle group, and the hamstrings generate the greatest force of any lower extremity muscle (Mann *et al.,* 1986). In particular the hamstrings undergo eccentric load when decelerating during the last third of the swing phase. This occurs in order to decelerate knee extension, allowing a greater force in the hamstrings than in the quadriceps. After foot contact occurs, eccentric muscle actions are ended, and the hamstring muscle group begins generating large quantities of concentric activity (Mann *et al.,* 1986). The extent to which the lower limbs are affected is unknown, and whether this affects bowling performance has seen little attention. Further, how bowlers perceive these musculoskeletal demands and the effect that this perception has on players has also received little attention in past research, and may lead to a better understanding of fatigue patterns in these players.

An understanding of how these musculoskeletal effects then influence bowling performance is important. While there are many definitions for performance of fast bowlers, all incorporate aspects of speed and accuracy. Performance is defined as the ability to maintain ball release speed and bowling accuracy throughout a bowling spell (Taliep *et al*., 2003). During an ODI a fast bowler's accuracy and ball release speeds are used as indicators of performance (Lillee, 1977, Stretch and Goslin, 1987; Portus *et al*.

2000, Taliep *et al*., 2003). Further, success in higher standards of play for fast bowlers is gained in sustained pace and accuracy (Lillee, 1977).

STATEMENT OF THE PROBLEM

Although fast bowling has received relatively more research attention than batting, the literature has mostly focused on lower back biomechanics and spinal load. Few studies have focused on the demands placed on the lower limb musculature and how these demands link to the bowler’s perceived effort and performance. The main purpose of this study was therefore to measure the lower limb musculoskeletal changes (EMG and functional muscle strength), and perceptual (perceived effort and body discomfort) responses of fast bowlers during repeated ‘run-ups’ and deliveries, and to relate these to performance responses (ball release speed and accuracy of bowling).

RESEARCH HYPOTHESES

It was expected that muscle recruitment and functional strength of the lower limbs would decrease as a result of a fast bowling spell. It was further expected that perceived effort would increase over time. Combined, these effects would negatively affect ball release speed and accuracy.

STATISTCAL HYPOTHESES

1. Hypothesis 1: Strength Parameters

   The first null hypothesis proposed no difference in functional strength parameters as a result of a fast bowling spell.

$Ho: \mu FS_{PRE} = \mu FS_{POST}$

$Ha: \mu FS_{PRE} \neq \mu FS_{POST}$

2. Hypothesis 2: Muscle Recruitment

The null hypothesis proposed no differences in muscle recruitment as a result of a fast bowling spell.

a) Vastus Medialis

$Ho: \mu MA_{PRE} = \mu MA_{POST}$

$Ha: \mu MA_{PRE} \neq \mu MA_{POST}$

b) Vastus Lateralis

$Ho: \mu MA_{PRE} = \mu MA_{POST}$

$Ha: \mu MA_{PRE} \neq \mu MA_{POST}$

c) Semitendinosus

$Ho: \mu MA_{PRE} = \mu MA_{POST}$

$Ha: \mu MA_{PRE} \neq \mu MA_{POST}$

d) Biceps Femoris

$Ho: \mu MA_{PRE} = \mu MA_{POST}$

$Ha: \mu MA_{PRE} \neq \mu MA_{POST}$

3. Hypothesis 3: Perceived Effort

The null hypothesis proposed no differences in local ratings of perceived exertion (RPE) as a result of a fast bowling spell.

$Ho: \mu_{Per1}=\mu_{Per2}=\mu_{Per3}=\mu_{Per4}=\mu_{Per5}=\mu_{Per6}=\mu_{Per7}=\mu_{Per8}$

Ha: $\mu_{Per1} \neq \mu_{Per2} \neq \mu_{Per3} \neq \mu_{Per4} \neq \mu_{Per5} \neq \mu_{Per6} \neq \mu_{Per7} \neq \mu_{Per8}$

4. Hypothesis 4: Accuracy

The null hypothesis proposed no differences in accuracy as a result of a fast bowling spell.

Ho: $\mu_{Acc1} = \mu_{Acc2} = \mu_{Acc3} = \mu_{Acc4} = \mu_{Acc5} = \mu_{Acc6} = \mu_{Acc7} = \mu_{Acc8}$

Ha: $\mu_{Acc1} \neq \mu_{Acc2} \neq \mu_{Acc3} \neq \mu_{Acc4} \neq \mu_{Acc5} \neq \mu_{Acc6} \neq \mu_{Acc7} \neq \mu_{Acc8}$

5. Hypothesis 5: Ball Release Speed

The null hypothesis proposed no differences in ball release speed as a result of a fast bowling spell.

Ho: $\mu_{Sp1} = \mu_{Sp2} = \mu_{Sp3} = \mu_{Sp4} = \mu_{Sp5} = \mu_{Sp6} = \mu_{Sp7} = \mu_{Sp8}$

Ha: $\mu_{Sp1} \neq \mu_{Sp2} \neq \mu_{Sp3} \neq \mu_{Sp4} \neq \mu_{Sp5} \neq \mu_{Sp6} \neq \mu_{Sp7} \neq \mu_{Sp8}$

WHERE:

- PRE = Pre-protocol
- POST = Post-protocol
- FS = Functional strength
- 1, 2, 3, 4, 5, 6, 7, 8 are the number of overs included
- MA = Muscle activity
- Per are the local RPE ratings
- Acc = Accuracy
- Sp = Speed

DELIMITATIONS

The study was delimited to 24 male fast bowlers between the ages of 19 and 24 years. All players were recruited from the Rhodes University, Grahamstown, South Africa Internal league teams.

Players were required to attend two sessions 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 and anthropometric data including age, body mass and stature, along with injury history were obtained. All players, no matter the experience, were habituated to all equipment used in both conditions, particularly to the treadmill and vertical jump board. 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. Performance measures (Accuracy and Ball release speed), and all perceptual scales used in the study were explained in the habituation session. The accuracy scoring zones were explained at the initial session, and again before testing

The second session involved the player performing the cricket-specific 8-over fast bowling protocol. All testing occurred under standardised conditions in two separate laboratory settings, in close proximity to each other. One setting was used for the treadmill protocol, during which muscle activity was measured and recorded, and the other setting was used for the actual protocol. Each player was assessed by the same researcher, and the dependent variables of interest were muscle activity, functional strength, perceived effort, body discomfort and performance.

LIMITATIONS

Although a conscious effort was made to control all possible variables which could have a role in affecting the results, a few of the following may have posed limitations to the study, and therefore must be considered when examining the results:

- Players were required to wear non-spiked shoes, which is not what players are used to, and which could have impacted the maximum speed bowlers were capable of producing.

- Testing took place in a laboratory setting to avoid the influence of extraneous environmental factors. Further, ambient temperatures were recorded on the days of testing, and testing only took place in an environmental window of 17 ° C to 28 ° C.

- Limiting the players' run-ups to reduce variability in results may have resulted in changes to the players' normal and natural speed and accuracy. To reduce the impact this had, pilot studies were performed to gain the best range which would incorporate the greatest number of players. Pilot studies indicated that most of the players were already within these ranges.

- In a real match, bowlers will not always aim for the wickets, and the accuracy board used in this study focused mainly on the wickets as the most accurate area. Bowlers often bowl wide of the wickets and use swing to 'set up' wickets. This limitation needs to be acknowledged.

- The accuracy board did allow for some inclusion of line and length, even though some balls were full tosses. This can be seen as a bad ball, while still achieving the maximum score for accuracy.

- This study was conducted within a laboratory setting, and as such was not able to incorporate all aspects of a cricket game. There were no team pressures, bowlers not bowling for a team and other factors such as motivation and responsibility were hard to replicate accurately. The absence of a batsman, as well as emotions that come with bowling to batsmen was also a limitation. Batsmen respond differently to each delivery, bowlers work on these inputs and may bowl differently to different batsmen. After taking a wicket, ball release speed and accuracy may differ from the results obtained in a laboratory setting.

- Time motion analysis helped determine the time between balls. In real match conditions the time between balls is, however, not consistent. To incorporate this, players were allowed ‘leeway’ between balls, as long as the over was completed in the set time.

- Bowling has both vertical and horizontal vectors; a horizontal and vertical jump test may have mapped power changes more accurately.

- Wide balls and slower balls were not taken into account. During real match play, bowlers would bowl an additional ball for a wide. Bowlers would also vary pace during a bowling spell. In this investigation bowlers were required to bowl as accurately and as fast as possible for each delivery.

- Many of the players were accustomed to bowling long spells, such as eight overs in a row. Others were not accustomed to this. This may have affected the results.

- Players were requested not to perform strenuous exercise, consume alcohol, and take unnecessary medication 24 hours prior to testing. However, if players had, testing was rescheduled for another occasion. This relied on the honesty of the players.

- Players were habituated to the surface in the Kingswood College high performance centre, and bowling on a different surface (texture and colour) even if cricket-specific, may have affected the player.

- Although fast bowlers use different techniques when bowling, due to the limited availability of fast bowlers, the technique was not controlled. Bowling style may cause differences in muscular, perceptual or performance measures.

- It is well known that surface EMG places certain limitations on testing. EMG measures the superficial muscle activity, and has limitations in dynamic muscle activity measurement, and the consistency of standard electrode placement.

- The normalization protocol was based on previous intermittent sports, soccer specifically. The normalization protocol used four separate speeds to asses pre- versus post-protocol muscle activity. Fast bowlers however change in speed during the delivery and all speeds are incorporated as in the normalization protocol. However the protocol fails to incorporate movements of a stop/start nature requiring acceleration and deceleration. Therefore the very high eccentric activity levels were missed.

- Another limiting factor, which was as a result of time constraints and access to the required players, is that the protocol was performed only once by each fast bowler. However, responses in players were similar to previous studies on fast bowlers. It is therefore likely that repeated measures were not necessary.

CHAPTER II

REVIEW OF LITERATURE

INTRODUCTION

Although cricket is one of the oldest organized sports, surprisingly little research has been afforded the game (Woolmer *et al*., 2008; Christie, 2012). Fast bowling, in particular, is a physically demanding activity requiring both physical fitness and high levels of skill and concentration. The demands of fast bowling and the associated levels of fatigue are not well understood, and despite the many theories, and suggested mechanisms for fatigue in these players, the physical demands placed on these players has not been fully elucidated.

NATURE OF THE GAME

Cricket is considered a team sport consisting of eleven players, however not all players are required to be on the field at one time. This is dependent on the team's task, either batting or bowling. If the team is the batting side, only two players will be on the field. If the team is the bowling side, all 11 will be on the field together. One player will be bowling, one will be wicket-keeper, and the remaining nine will be strategically placed as fielders. Players are selected for the team based on specific skills in the bowling, fielding or batting fields of the sport, all adding input towards the team's overall versatility and effectiveness. The biomechanical, physiological and perceptual demands placed on the individuals in each domain are considerably varied, making it important to investigate the demands on the players in each position.

MOVEMENT PATTERNS

Time-motion analysis is a method of research used to gain a better understanding of the physical demands of cricket (Duffield and Drinkwater, 2008). Time motion analysis helps acquire data on the frequency, mode and duration of player activities. Recording the duration of time during each specific movement, such as time per over, time between overs, and time per delivery. Through this method of research, improved training specificity and enhanced physiological adaptations can occur, thus resulting in an overall improved performance (Duffield and Drinkwater, 2008).

Global Positioning System

Petersen *et al.* (2010) observed movement patterns of players *in situ,* using global positioning systems (GPS). Fast bowlers, in comparison to batsmen, fielders and wicket keepers, covered the greatest distance. Fast bowlers were observed to cover 13.4 (±0.7) km per match, Batsmen 8.7 (±0.6) km, and wicket keepers 9.5 km (Petersen *et al.,* 2010. Additionally, fast bowlers covered the highest distances when striding and sprinting; batsmen covered 0.5 km, and wicket keepers 0.1km at an all-out sprinting intensity, while fast bowlers covered 1.1 km at all-out sprinting intensities, during each match (Petersen *et al.,* 2010). However movement path and intensity significantly influenced the reliability and validity of data obtained via GPS (Gray *et al.,* 2010). During all-out sprint intensities, GPS measurements underestimate total distance covered (Gray *et al.,* 2010).

Gray *et al.* (2010) assessed movement intensities and path linearity on GPS distance, accuracy and reliability. Distance covered was slightly overestimated with all movement intensities, sprinting and walking intensities showing the highest overestimates, when movement patterns followed a linear path (Gray *et al.,* 2010). GPS measurements are considered reliable; however, this reliability was reduced when it came to all-out sprinting intensities (Gray *et al.,* 2010). A run-up for fast bowlers is linear. This would suggest that, for fast bowlers, GPS was able to provide accurate, valid and reliable data, with no more than a 5% total distance error (Coutts and Duffield, 2010).

TYPES OF MATCHES

Originally cricket was played as a Test match over five days. One day matches were developed later, introducing over limits for bowlers and intensifying the game. In recent years there has been a new development, with the introduction of Twenty20 (T20) matches. T20 matches consist of 20 overs being bowled by each team. These games are more concise and crowd appeasing.

Each side will stop bowling when 10 of the 11 batsmen have been dismissed. During Test match cricket, there are no restrictions placed on the number of overs, by each bowler and the bowling side as a whole. If both teams are dismissed within the five days of play, a second innings commences during which both teams have the opportunity to bat and bowl again. The runs obtained by teams in the first innings are carried forward into the second innings (Woolmer *et al*, 2008).

One day matches were introduced in 1971, and this form of the game has attracted many more spectators, as it is faster, and more attractive to fans (Woolmer *et al*, 2008). One day matches take place over a single day. Each team is required to bowl until the opposing team is dismissed, or the over limit of 50 has been reached. Bowlers are restricted to 10 overs each, in this form of the game.

Twenty20 (T20) matches are played to a maximum 20 overs per team, or until the batting side has been dismissed. This form of the game was introduced in 2003, and has become increasingly popular. Restrictions in this game are twofold, namely with regard to time, and restrictions on the bowlers. Bowlers are restricted to four overs each, with a total of 20 overs bowled per match.

PLAYERS

Batsmen

Batting is a technique which is difficult to learn, and to master. A good batsman will correctly judge the length and line of each ball, and have the ability to move quickly and easily around the crease. Batting entails striking a ball to generate runs and prevent the ball from hitting the stumps, with the use of a cricket bat. Batsmen generate runs by hitting the ball over the designated boundary line. If the ball is hit over the boundary line with no bounce, six runs are awarded. Hitting the ball over the boundary having bounced will result in four runs being awarded to the batsman. Alternatively, and more commonly, batsmen generate runs by hitting the ball into gaps in the field, to gain enough time to "sprint" to the other crease. One run is generated by the (two) batsmen running from one crease to the other and making contact either side of these creases.

There are only two batsmen on the field at a time, one of these batsmen being on strike during each delivery. Batsmen stand on either side on the pitch and run between the wickets to accumulate runs. Batsmen in an entire ODI covered 8.7+0.6 km, with 0.5 km covered at sprinting intensity (Petersen *et al.,* 2010). Once a batsman is dismissed, the next batsman will enter the field. This process occurs until 50 overs have been accomplished, or ten wickets have been taken. The batting side's score is then displayed, and the fielding side now has a target which must be reached, to win the match.

Fielders and Wicket-Keeper

The main objective of the fielder is to collect the ball, after it is hit by the batsman, so as to either limit the number of runs the batsman scores, or get the batsman out by catching the ball before it bounces. Alternatively, a fielder can dismiss the batsman by run-out, throwing the ball onto the stumps, before the batsman can cross the crease. A fielder may field the ball with any part of his person. The captain has the task of placing the fielders into positions around the field. Which positions are filled by players is a tactical decision made by the captain, depending on the nature of the match. Strategic placement of fielders can often lead to wickets being taken, and players are positioned in ‘common’ hitting areas.

The wicket-keeper is positioned behind the stumps on the strikers side of the pitch. The wicket-keeper has many demands placed on him during a match. Physically the wicket-keeper must be ready to field on every delivery, squat before and during each delivery, and after each ball is bowled run to the stumps (Woolmer *et al.,* 2008). A wicket-keeper can travel on average 9.5 km, and cover 0.1 km at sprinting intensity (Petersen *et al.,* 2010). Mentally the wicket-keeper has to encourage and advise the bowlers, and identify any problems. The wicket-keeper must stay completely focused: at any point there may be a catch or a run-out opportunity, without time for anticipation. The wicket-keeper is required to have good reaction time (Woolmer *et al.,* 2008).

Bowlers

There are many different categories of bowlers. Depending on the captain, and tactics being used, bowlers will be strategically selected. There are fast bowlers, medium paced, and spin bowlers. Medium pace bowlers have shorter run-ups, and use swing and accuracy to make up for the lack of pace. Medium pacers are normally accurate and are used to make the batsmen focus on defending rather than making runs (Woolmer *et al.,* 2008). Spin bowlers are much slower when it comes to pace of the delivery. Spin bowlers force the batsmen to play more risky shots in the air, and increase the chance of taking wickets. Spin bowlers cause the ball to bounce at an angle off the pitch, forcing the batsman to treat each ball carefully. Fast bowlers are characterized by their speed, and long run-ups, with batsmen being limited by shot selection based on reaction time, often leading to costly mistakes.

Fast bowling can be divided into 3 distinct phases: The run-up, the delivery, and the follow through. Each phase involves distinctly different movements and muscle recruitment patterns. Two essential phases of fast bowling are the run-up and the follow through (Noakes and Durandt, 2000). These two phases involve the bowler accelerating to maximum momentum, and decelerating to a standstill in a very short space of time. These two phases elicit the largest volume of eccentric muscle action in the lower limbs (Noakes and Durandt, 2000), therefore playing an integral part in the understanding of the fatigue mechanism during fast bowling.

INJURIES IN CRICKET

Injury surveillance is a vital process when furthering research into cricket (Stretch and Raffan, 2011), and can directly lead to successful injury prevention programmes being developed. Further, research into the mechanisms that lead to these injuries are important for understanding overall fatigue, and injuries caused by fast bowling in particular.

Long-term injury studies have been done in Australia, South Africa and England to identify injury patterns (Leary and White, 2000; Orchard *et al*., 2002; Stretch and Venter, 2005). In these studies, injury was defined as the beginning of pain or disability directly caused by training, or playing cricket, and which caused the player to seek medical attention (Stretch 2007). The majority of injuries in cricket were observed in bowlers (Table I), and primarily in the lower limbs of bowlers.

In Australia, retrospective studies between 1995 and 1998 showed that 886 injuries occurred, with 92% of these being first-time occurrences. The injuries were mainly sustained while bowling (45%), with lower limb injuries accounting for 49% of injuries (Table I) and trunk, neck and head for 25% of these injuries. Of these injuries, 72% where as a result of muscle/tendon strains (Stretch *et al.* 2009). Fast bowlers missed approximately 16% of potential playing time because of injuries, whereas the potential playing time missed by other players was seen to be as little as 5% (Orchard *et al*., 2002; Stretch and Raffan, 2011).

In South Africa between 1998 and 2004, 1606 injuries were recorded, first-time injuries accounting for 65% of the total. Similar to findings proposed by Orchard *et al* (2002), bowling accounted for the majority of injuries (40%). The majority of injuries to fast bowlers occurred in the lower limb, accounting for 55% of injuries (Table I), while back and trunk injuries accounted for a further 33% of injuries in bowlers (Stretch and Venter, 2005).

A retrospective study done in England between 1985 and 1995 showed a total of 990 injuries. Bowlers were observed to have the highest injury incidence, 70.1 injuries per 1 000 days (Leary and White, 2000). The majority of injuries occurred to the lower limbs (45%), in agreement with previous findings (Leary and White, 2000; Orchard *et al.*, 2002; Stretch and Venter, 2005).

Table I: Injuries in cricket of three leading cricketing countries

	Total Injuries	**Bowling**	**Lower Limb**	**Time Period**
Australia	886	45%	49%	1995-1998
South Africa	1606	40%	55%	1998-2004
England	990	70.1 injuries per 1000 days	45%	1985-1995

Lower limb injuries in cricket are predominantly hamstring, quadriceps and calf muscle strains directly attributable to all-out sprint efforts (Payne, 1987; Stretch, 1989; Stretch, 2001; Brooks *et al.*, 2005). Bowling, batting and fielding require both stop-start movements and many changes in direction of the whole body. During an all-out sprinting effort, the hamstring muscle group is activated during the last third of the swing phase, which is during terminal swing for sprinting (Schache, *et al.,* 2010). Changes in body direction, and constant acceleration and deceleration, require strength, agility and flexibility. In high intensity sports involving a high concentration of stretch-shortening cycles, it has been suggested that the inclusion of a stretching programme significantly influences the viscosity of the tendons, making them more compliant. This suggests that stretching may be beneficial for injury prevention (Stretch *et al.*, 2009). So, while the lower back has been the focus of a vast amount of injury-related research on fast bowlers, and rightly so, there has been a tendency to neglect the load placed on the lower limb areas which are most frequently injured.

Immediately after a muscle strain injury, hamstrings demonstrate a negative response to complete eccentric muscle actions (Schache, *et al.,* 2010). Injury risk is increased by a weakness in the hamstrings. There is often an imbalance between the hamstrings and the quadriceps strength: this is known as the hamstring: quadriceps ratio (H:Q) (Aagaard *et al.*, 1998). A large difference between the hamstrings and quadriceps strength indicates increased risk of injury (Clark, 2008).

In addition to large numbers of lower limb injuries, bowlers experience a number of collisions (impact at rear-foot and front-foot) with the ground during each delivery. The largest impact with the ground is seen at front-foot strike with peak forces of approximately five times a player's body weight (BW) being generated vertically, and forces twice the BW generated horizontally (Foster *et al.*, 1989). Simultaneously, the trunk experiences hyperextension, lateral flexing and twisting, which is adopted to enable the bowler to perform maximum delivery speed (Burnett *et al.*, 1995).

BOWLING PROCESS

The run-up

The run-up involves bowlers reaching maximum momentum while still maintaining control, with no set run-up distance. There are many variations in a fast bowler's run-ups. Fast bowlers may start the run-up with lots of fast small steps, walking or reaching full pace in one or two strides, and as such, there is no set method to adopt during a run-up (Woolmer *et al.,* 2008). Running requires repeated activation of the hamstring muscle group. The hamstrings are recruited during the last third of the swing phase. Eccentric muscle action occurs to decelerate knee extension, and allow the hamstrings to counter-act the force produced by the quadriceps muscle group (Mann *et al.,* 1986). High levels of eccentric muscle activity occur until initial foot contact, at this stage concentric muscle activity increases in the hamstrings (Mann *et al.,* 1986). It is therefore well known that the run-up requires large amounts of muscle activation during the acceleration phase. This continuous and repeated acceleration places stresses on the lower limb muscles. Eccentric muscle actions are very efficient while generating forces, although these actions cause a higher strain placed over fewer muscle fibers (Komi, 2000; McHugh *et al.*, 2000). Eccentric actions are heavily involved in sprinting (Mann *et al.*, 1986), which is an integral part of the bowling movement.

The delivery

The bowler identifies the target line; the bowling arm is then moved up and swings around in a circular manner. There is a sudden twisting in the hips which generates the force required to propel the ball; the ball is released at the top of the arc above the bowler's head. The delivery stride involves the player landing on the back foot, followed by lateral flexing, rotation and hyper-extension of the trunk (Foster *et al.,* 1989). Large forces are experienced in the front foot and lower back during this delivery stride (Elliot *et al.,* 1992). After the ball is released the arm continues in a circular manner, which is better understood as part of the follow-through (Woolmer *et al.,* 2008). It is particularly important for the bowler to keep an eye on the target during the run-up, to develop an efficient technique and increased accuracy (Lillee, 1977; Australian Cricket Board, 1998). The final ball release is joined with foot contact; the front foot of the bowler is required to break the bowler's momentum, from full momentum gathered during the run-up. This places a large eccentric load on the limb. Studies indicate fast bowling requires players to absorb vertical forces of 4.1 times their body weight, and horizontal deceleration forces of 1.6 times their body weight at foot contact (Elliott *et al.,* 1986).

The follow-through

After the ball is released, the follow through has begun. The bowling-arm continues along its circular path. During the follow-through the bowler continues to decrease speed, to a complete standstill in a few steps. This deceleration requires large amounts of eccentric muscle action. The activated muscles must exert a braking force to control the motion of the body. While obtaining full speed and reducing speed, eccentric actions play a vital role (Whitehead *et al*., 1998). Large amounts of eccentric muscle activity are directly linked to a reduced force production, or associated with shifts in optimal muscle length, increase in passive tension and changes in neuromuscular control (Clarkson and Hubal. 1992; Enoka, 1996; Fridén and Lieber, 1992; Byrne *et al*., 2004). The fast accelerations and decelerations may be one of the main contributing factors to fatigue in fast bowlers, and reduced performance.

FAST BOWLING ACTIONS

There are many different techniques to fast bowling, the three most common of which are known as side-on, front-on, and mixed action, while some bowler's have different techniques, making it hard to classify. However, the majority of fast-bowlers can be placed into one of these bowling categories.

Side-on

The side-on action is considered the most common and traditional method of bowling (Woolmer *et al.,* 2008). The action is characterized by the body being in a sideways position; more specifically, the hips and the shoulders are aligned. The back foot impact during this action involves no major deviation during the delivery. The bowler will watch the batsman and the crease over the front shoulder. There is a slight but sudden force generation as the hips twist during the delivery (Portus *et al*., 2000; Woolmer *et al.,* 2008). A good side-on and front-on technique allows the bowler to maintain eye contact throughout the delivery and follow-through, and limited counter-rotation of the shoulders can be observed. Counter-rotation of the shoulders is suggested to decrease accuracy of a fast bowler, as stability is inhibited, and eye contact restricted (Portus *et al*., 2000). In fact reports suggest that shoulder rotation can result in up to a 29 percent (%) reduction in bowling accuracy (Portus *et al*., 2000).

Front-on

A front-on action is characterized by the bowler's feet pointing down the pitch, and the shoulders and hips aligned diagonally across the pitch (Portus *et al*., 2000). The bowler's chest faces the batsman during the run-up and delivery. There has been criticism of this front-on action, as it is harder to generate swing of the ball during deliveries (Woolmer *et al.,* 2008).

Mixed Action

A mixed fast bowling action has been observed to produce the highest incidence of injury, specifically lower back injury (Foster *et al*., 1989; Elliot *et al*., 1992). Placing large amounts of torsional load on the lower back proves to be detrimental, as this leads to the highest incidence of injury in fast bowlers, injuries such as pars interarticularis stress fractures, intervertebral disc degeneration, bone bruises and fractures (Burnett *et al*., 1991, Foster *et al*., 1989; Elliot *et al*.,1992; Stretch *et al*., 2000; Woolmer *et al.,* 2008; Foster *et al*., 2011). The mixed action involves a more frontward approach when bowling, with regard to hip position, and a more side-on approach with regard to the shoulder positioning, or *vice versa* (Portus *et al*., 2000). The combination of front-on and side-on postures in the same bowling action is considered dangerous (Portus *et al*., 2000). The bowler lands on the back foot during the delivery and is required to twist into position during the delivery, placing extreme pressures on the lower back, as the hips and shoulders rotate in opposite directions (Portus *et al*., 2000; Woolmer *et al*., 2008).

MUSCLES INVOLVED IN FAST BOWLING

Upper Body

To the author's knowledge there have been relatively few studies conducted on the demands placed on the upper limbs of fast bowlers. This is despite the fact that upper limb injuries have been reported to account for 23.3% of injuries, which is almost that of the lower back and trunk (22.8%) (Stretch *and* Raffan*.,* 2011).

By breaking down the movement stages of a fast bowling action the muscles involved in each stage of motion can be isolated and the specific movement determined. Acknowledging that multiple muscles are involved with each element of the delivery, the following are the primary movers in each instance. Trapezius activates the initial lift of the arm, and the deltoids are activated thereafter to rotate the bowling arm around the shoulder. This is followed by the pectoralis major, which drives the fast frontal pull of the arm (Woolmer *et al.,* 2008). Latissimus dorsi, in conjunction with the anterior deltoid, engages to complete the swift downward pull of the arm as the ball is released (Aginsky *et al.,* 2004). Additional muscles driving the bowling action include the biceps, wrist flexors, teres major and teres minor, as well as several muscles connected with the "rotator cuff". Bloomfield *et al*. (1994) suggested that fast bowlers could increase ball release speed simply by increasing strength and power, especially in the trunk and shoulder regions.

Trunk

Fast bowling demands high-speed twisting of the trunk with simultaneous forward impetus. As a result lower back injury and discomfort is frequently noted in specialist fast bowlers (Dennis *et al.,* 2005). Previous research has paid attention to the following muscles in this regard: quadratus lumborum (QL) (Engstrom *et al*., 1999, Engstrom *et al*., 2007, and Walker *et al*., 1999); external obliques (EO), internal obliques (IO), rectus abdominis (RA) (Springer *et al*., 2006) and transversus abdominis (TrA) (Springer *et al*., 2006; Tesh *et al.,* 1987; Hodges *et al*., 2003; Hodges *et al.,* 2005; Barker *et al.,* 2006), which are all recruited at the same stage in the fast bowling action, either to initiate or sustain movement or to stabilize the trunk.

O'Sullivan *et al.* (1997) reported that the lumbar spine is at risk of injury because of different loading conditions, which could be caused by muscle imbalances. Spinal stability is achieved through an appropriate interplay between large torque-producing muscles, such as the RA and EO, and those muscles better designed to provide control and stability to the lumbar spine, such as the multifidus, QL, and TrA. TrA supports, stabilizes and protects the lumbar spine during the fast delivery, and is thus the muscle that has received the greatest focus in previous research studies (ref).

Lower Body

Given the noticeable twists and speed of the fast bowling delivery, most attention has been dedicated to the upper body and torso. The contribution of the lower body has been underestimated, particularly as fast bowlers are required to accelerate to full forward drive followed immediately by rapid deceleration. Gaining momentum and stopping it within a matter of a step or two generates high stress in the lower extremities, and in particular at the joints. The muscle groups most prominantly involved in sprinting are the quadriceps (rectus femoris, vastus lateralis, vastus medialis and vastus intermedius muscles) and the hamstrings (biceps femoris, semitendinosus and semimembranosus) (Pincivero *et al*., 2000). Sprinting depends largely on eccentric muscle actions (Mann *et al*., 1986), and the force absorbed by the impact of the front foot at the moment of delivery creates further risk to lower extremities. Sprinting and braking are associated with high danger of hamstring injury. The hamstring group decelerates knee extension by activating in an eccentric manner. By doing so, the action of the quadriceps group is also opposed, causing an abrupt change from maximal eccentric to maximal concentric muscle activation, which in turn maximizes the force experienced at the level of the lower limbs. For the purposes of evaluation the vastus lateralis and vastus medialis are monitored to represent quadriceps group action, while the biceps femoris and semitendinosus muscles represent hamstring activation.

MUSCLE ACTION IN FAST BOWLING

The stretch-shortening cycle (SSC) of muscle occurs when muscle undergoes stretch during activation (eccentric action), followed by an immediate shortening (concentric action) of the muscle (Komi, 1984; Komi, 2000). In relation to fast bowlers, SSCs occur throughout a bowling spell. During fast bowling bowling running, jumping and sprinting, all result in SSC of muscles in the lower limbs (Norman and Komi, 1979; Komi, 1984; Komi and Nicol, 2000). SSC muscle function serves to increase concentric force after the stretch phase, in comparison to isolated concentric actions (Cavagna *et al.,* 1968; Komi, 1983). The increased force is often presented as an increased concentric performance which is achieved as a result of an increased final propulsive shortening action, in comparison to an isolated shorting action (Byrne *et al*., 2004).

ECCENTRIC MUSCLE ACTIVITY

Eccentric muscle actions involve the mechanical detachment of proteins: actin and myosin, as the muscle fibres are lengthened during the lengthening muscle action (Flitney and Hirst, 1978). Eccentric muscle actions cause overstretching of sarcomeres beyond the optimum length (Morgan and Allen, 1999). The space between intermediate filaments may be compromised by this muscle lengthening, causing morphologic muscle adaptations. The reduction in force generation following an eccentric exercise bout may be associated with morphologic changes such as Z-disc disruption (separating and linking sarcomeres in muscle) (Waterman-Storer, 1991); damaged myofibrils, torn sarcolemmas (Tortora and Derickson, 2006); excitation-contraction coupling failure, selective muscle fibre damage and altered sarcomere lengths (Morgan and Allen, 1999; Proske and Morgan, 2001).

Eccentric exercise causes major structural changes to the muscle tissue (Waterman-Storer, 1991; Byrd, 1991; Tortora and Derickson, 2006). Dilation of the SR; decreased calcium regulation (decreased uptake rate of calcium, and decreased release rate of calcium); sarcolemmal disruption, fragmentation of the sarcoplasmic reticulum and swollen mitochondria (St Clair Gibson *et al.*, 1998; Fridén and Lieber, 1992). The decreased calcium regulation is directly responsible for the heightened level of intracellular calcium. The increase in this concentration would activate proteolytic enzymes, which may result in the myofibril damage, and causing further structural protein degradation (Waterman-Storer, 1991). However the pathways to the myofibril damage are not fully understood (Waterman-Storer, 1991; Byrd, 1991). Structural changes may be responsible for the temporary reduction in muscle forces (Waterman-Storer, 1991). A reduction in muscle force is known as fatigue. In any sport, and more specifically cricket, if players are unable to produce the needed force, performance may be affected. The extent to which structural changes, and ultimately fatigue, occur are not well understood in cricket, therefore more research on the extent of damage to the lower limbs, as a result of repeated eccentric actions, should be further investigated.

FUNCTIONAL CONSEQUENCES OF ECCENTRIC ACTIONS

Functional consequences following eccentric muscle action include: Reduced force production, shifts in optimal muscle length, increase in passive tension and changes in neuromuscular control (Clarkson *et al.,* 1992; Enoka, 1996; Fridén and Lieber, 1992; Byrne *et al.*, 2004).

Force Loss

The mechanism by which force is lost following repeated eccentric contractions has not been clearly established. Strength losses, however, are evident following eccentric activities. Strength losses are considered reliable indicators of exercise-induced muscle damage (Warren *et al*., 1999; Clarkson *et al*., 2002). Eccentric actions result in a greater force decrease following the work-bout, as well as a longer recovery period in relation to activities using other muscle actions more predominantly (Clarkson *et al*., 2002). Concentric actions also result in decrements in force following exercise. Damage was however observed for only a few hours (Warren *et al*., 1999). Research on eccentric peak hamstring torque showed large decrements as a result of a soccer-specific protocol (Greig and Siegler, 2009). Results indicated that the hamstring musculature had deteriorated such that the player was exposed to a higher chance of muscular strain and impaired joint stability following the protocol (Greig and Siegler, 2009). Intense eccentric exercise (maximal or near maximal eccentric actions) sustained up to a 50-65% loss in ability to generate force in comparison to values prior to protocol (Saxon *et al*., 1995). Eccentric peak torque in the hamstrings has been noted to significantly decrease after players perform a rugby-specific protocol (Christie and Brown, 2009). The ability to generate force will have an impact in any intermittent sport, with the major implications being that a player’s ability to accelerate will decrease, and deceleration time will increase. The muscles involved in performing each delivery, especially in fast bowlers, are of crucial importance. If these muscles, particularly those associated with accelerating and sprints, are unable to produce the required levels of force, speed will decrease, and as speed is an important part of performance for bowlers this will negatively affect fast bowling performance.

Optimum Length Tension Relationship

The length tension relationship refers to the length of the sarcomeres before contraction begins. This relationship indicates the forcefulness, and how it is dependent on the length of the sarcomeres. Resting muscle fibre length is held close to the optimum, and can produce maximum forces when activated (Tortora and Derickson, 2006). It has been concluded that eccentric exercise results in a shift in this optimum length (Enoka, 1996; Byrne and Eston, 2002 and Nosaka *et al*., 2002). A shift in the optimum length is particularly important, as it is considered a reliable indicator of muscle damage, and the extent of shift directly correlates to the extent of muscle damage (Jones *et al*., 1997). Bowers *et al*. (2004) presents similar correlations with increased exercise intensity and exercise volume. This was directly related to greater shifts in optimum sarcomere length (Bowers *et al*., 2004). The implications of a shift in the optimum length of sarcomeres in sports are vast. A shift in optimum length causes a shortened overlap between the actin and myosin proteins; therefore the tension that the muscle fibres can generate is decreased (Tortora and Derickson, 2006). The inability to produce adequate force will decrease performance in fast bowling. Accelerating to high speeds is vital for maintaining ball release speed and performance. If adequate forces cannot be achieved performance will be directly affected.

Passive Tension

Following a bout of eccentric exercise there has been shown to be a resultant increase in passive tension (Proske and Allen, 2004). It is suggested that local damage following eccentric exercise results in an inflammatory response and increased levels of extracellular fluid (Smith, 1991). These developments lead to strained passive elastic elements in the muscle, resulting in the rise of passive tension (Howell *et al.,* 1993). This theory is unable to fully account for the rise in passive torque. The main problem is that the order of responses and the time following the eccentric exercise do not correspond. Muscle elicits significant inflammation after 24 hours, and peak values were shown at 48 hours after the exercise. Passive tension after 24 hours had already reached peak, while after 48 hours had started to decline (Whitehead *et al*., 2001).

Another theory indicated the passive tension increasing as a direct result of an altered sarcomere distribution, and membrane damage occurring in the sarcoplasmic reticulum, following eccentric muscle activity (Enoka, 1996). The origin of increased passive tension is associated with the elastic filaments composed of the protein titin in the sarcomeres. Titin is a structural protein that links Z-lines to one another, and the increased strain on titin causes strain on the Z-lines. This results in an increased passive tension (Whitehead *et al*., 2001). Shortening sarcomeres cause an added strain on adjacent areas, increasing the passive tension as well as the likelihood of injury (Proske and Allen, 2004). Increased risk of injury is of high importance in intermittent sports. Passive tension mechanisms leading to injury should be further studied, so as to gain further insights into this field, thus allowing injury minimization intervention programmes to be conducted.

Neuromuscular Fatigue and Force Production

There have been limited studies focused on the effects of intermittent activity on neuromuscular control. The studies which have been done on intermittent sports such as soccer, rugby, tennis and squash have all shown similar significant reductions in maximal stretch shortening cycles, concentric and eccentric forces and EMG activity of lower limb musculature (Rahnama *et.*, 2003; Grieg, 2008; Girard *et al.*, 2008; Grieg and Siegler 2009; Girard et al., 2008, Christie and Brown, 2009). Girard *et al.,* (2008) showed the impact of a three-hour intermittent tennis protocol on neuromuscular fatigue. Significant torque losses of 10-13% were observed. Towards the end of the protocol the largest decrements in normal EMG activity were observed.

Muscle damage as a result of repetitive stretch shortening activity is associated with extended reductions in maximal force generation and muscle activity (Avela *et al.*, 1999). During a rugby-specific protocol EMG activity of the semitendinosus decreased significantly as a response to the intermittent condition (Christie and Brown, 2009). Muscle activity of the biceps femoris was also shown to decrease over time. These results indicate that muscular fatigue was induced by the stop-start nature of the protocol, particularly in the hamstring musculature (Christie and Brown, 2009). Eccentric movements and activities causing muscular damage are associated with a loss of force and limited motor control. Previous research following a bout of eccentric activity has shown similar decreases in force and EMG activity (Byrne *et al.,* 2004), representing a reduced level of neuromuscular efficiency (Saxon *et al.,* 1995; Byrne *et al.,* 2004).

FATIGUE

Fatigue is the inability to regenerate or recreate an original force, causing a decrease in force production (Bigland-Ritchie, 1983; Gandevia, 1998). Fatigue can be divided into two main categories: central and peripheral fatigue depending, to some degree, on the task characteristics (Enoka, 1996 and Girard *et al*., 2008). Changes within the motor unit correspond to peripheral fatigue, whereas changes within the brain and spinal cord correspond to central fatigue (Asmussen, 1979). Characteristics of both central and peripheral 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 and Durandt, 2000). This delayed stretch-shortening cycle would decrease performance, particularly during intermittent activities (Nybo and Secher, 2004). During continuous dynamic exercise, it becomes harder to determine whether central or peripheral factors are contributing to fatigue (Nybo and Secher, 2004). Fatigue has also been suggested to occur as a safety mechanism to the human body, controlled by central or peripheral fatigue components. The central regulation of exercise intensity has been suggested to occur in order to stop catastrophic failure to vital organs (Noakes *et al*., 2004; Lambert *et al*., 2005; St Clair Gibson *et al*., 2001; St Clair Gibson *et al.*, 2004; Tucker *et al*., 2004; Tucker *et al*., 2006), as well as an injury development or metabolic crisis prevention (Balasubramanian and Jayaraman, 2009). Evidence of the safety mechanism theory may be found in the lower rate at which central and peripheral fatigue occur at a sub-maximal exercise intensity (Taylor and Gandevia, 2008). While peripheral fatigue has been shown to occur during many different forms of exercise, some evidence suggests that central fatigue is the more common of the two (Skurvydas *et al*., 2010). Exercise has been suggested to be centrally regulated, as a response to neural integration of afferent information originating at the periphery, as well as being predisposed by factors such as previous experience and training (St Clair Gibson *et al*, 2004). Central fatigue occurs as a result of a reduction in the neural drive to the muscle and a decreased force production or tension development that is independent of, and unaffected by, changes in skeletal muscle contractility (Enoka and Stuart, 1992). Peripheral muscle fatigue occurs as a result of one or many factors occurring at the periphery: decreased capacity of the skeletal muscle to generate force resulting from action potential failure, excitation-contraction coupling failure, or impairment of cross-bridge cycling. All of these factors occurring without change, or increase in neural drive (Hakkinen, 1983).

The peripheral fatigue model has been commonly used to explain fatigue for the past several decades (Noakes and Durandt, 2000). Peripheral fatigue, located distal to the neuromuscular junction, causes a reduction in force and power production (Gandevia, 1998; Girard *et al*., 2008; Taylor and Gandevia, 2008). A specific metabolic event within the active muscle causes the reduction in contractility of muscle fibres (Kayser, 2003). This model suggests that system failure occurs because of either metabolite accumulation or substrate depletion, and can only be prevented by reducing the workload or completely terminating the exercise (Lambert *et al*., 2005). The factors mainly contributing to peripheral fatigue are excitation-contraction coupling failure, and metabolic inhibition of the contractile process (Kent-Braun, 1999). Failure in the excitation-contraction coupling is associated with prolonged periods of low-intensity exercise resulting in a slow time course of recovery (Kent-Braun, 1999). However, during high-intensity exercise, the accumulation of intramuscular metabolites, and the slowing of muscle relaxation have been associated with fatigue development (Gandevia, 1998 and Kent- Braun, 1999).

Central fatigue refers to the muscle fatigue as a direct result of the physiological process within the central nervous system (CNS), within sites proximal to the neuromuscular junction (Enoka, 1996; Girard *et al*., 2008; Taylor and Gandevia, 2008). The CNS is provided with information from various sites which are involved in exercise. The CNS can limit the intensity and duration of skeletal muscle recruitment, limiting exercise capacity of the individual, if there were any risk present (Davis and Bailey, 1997; Kayser, 2003; St Clair Gibson *et al*, 2004). The alteration in the neurotransmitter function within the brain is associated with three adaptations in the body: a reduction in the excitatory input, an increase in the inhibitory input and reduced responsiveness of motor neurons, causing a reduction in the ability to recruit the optimal number of motor units within a muscle (Girard *et al*., 2008 and Taylor and Gandevia, 2008).

The primary aim of central down-regulation of muscle output (intensity and duration), is to maintain whole-body homeostasis (St Clair Gibson *et al*, 2004). Intensity and duration can be reduced by progressive failure of voluntary muscle activation, associated with the slowing of motor unit firing rates (Taylor and Gandevia, 2008). Central fatigue has been suggested to play a major role in intermittent exercise, and reducing muscle force capabilities (Kayser, 2003 and Girard *et al*., 2008). However, because there is no clear differentiation between the nervous system and the exercising muscle (Barry and Enoka, 2007), it becomes unclear as to how the central and peripheral factors contribute to muscle fatigue during intermittent exercises (Morris *et al*., 1998; Girard *et al*., 2008).

QUANTIFYING FATIGUE

Strength Measures

Muscle strength and power measurements, including changes in strength and power, are essential in the assessment of performance, and of performance over time. Assessment methods include amongst others, isokinetic, isometric and isotonic tests which can be done within both a laboratory and/or field setting (Brown and Weir, 2001).

Isokinetic Testing

In some recent studies performed on cricket players isokinetic testing was used (Christie *et al., 2008;* Christie and Brown*,* 2009; Christie *et al*., 2010b; Christie and Sheppard*,* 2012). Isokinetic testing involves the assessment of maximal muscle peak torque, and work throughout a range of joint motion set at a constant angular velocity (Perrin, 1993). The isokinetic speeds of 60 deg.s^{-1} to determine muscular strength, and 270 deg.s^{-1}, which is a speed that more closely represents actions experienced during free exercise (Williams, 1994; Cometti *et al*., 2001; Nunes and Coetzee, 2007), are suggested to more accurately assess changes in strength in response to intermittent sports. The disadvantage of this type of equipment is that it is costly, non-portable plus is not dynamic in nature so its applicability in movement patterns experienced in cricket may not be accurately represented by leg extension and leg flexion strength testing.

Hamstring to Quadriceps (H:Q) ratio is commonly used to evaluate the muscle strength around the knee joint (Osterning, 1986; Baltzopoulos and Brodie, 1989; Gleeson and Mercer, 1996). The ratio is calculated by dividing maximal concentric knee flexors by the concentric knee extensors at a set joint angular velocity (Gleeson and Mercer, 1996; Aagaard, *et al.,* 1998). This H:Q ratio is known as the conventional concentric H:Q ratio. In recent years a more functional evaluation has been adopted. The antagonist-agonist strength relationship may be represented better by using a more functional ratio of: eccentric hamstring strength divided by concentric quadriceps strength, and/or alternatively concentric hamstring strength divided by eccentric quadriceps strength (Aagaard *et al.,* 1998). This ratio allows for functional and conventional data, as well as data on absolute muscle strength to be obtained. Functional ratio can be used to represent a more relevant estimate of the knee joint's stabilization capacity than the conventional H:Q ratio (Aagaard *et al.,* 1995; Aagaard *et al.,* 1996).

Vertical Jump

The Vertical Jump (VJ) test is a commonly used field test of muscle power in the lower limb musculature, and its reliability has been reported as high (Arteeaga *et al.*, 2000; Ashley and Weiss, 1994; Bosco and Viitasalo, 1982; Goodwin *et al.*, 1999; Harman *et al.*, 1990). VJ can be used to describe two different forms of jump: the squat jump (SJ) and the counter-movement jump (CMJ) (Harman *et al.*, 1991; Brown and Weir, 2001). Research on the SJ and CMJ suggest coefficient of variation scores to be 5.4% and 6.3 % respectively (Arteeaga *et al.,* 2000). The SJ has been suggested to be more reliable than the CMJ (Sayers *et al.*, 1999) as its technique is easily controlled; the CMJ involves uncontrolled movement which increases variability between individuals. Furthermore, regression equations result in more accurate estimates of power output when using SJ data than when CMJ data are used (Sayers *et al.*, 1999; Brown and Weir, 2001).

Prediction equations, which incorporate the SJ height and the individual's body mass (kg) are used to estimate an individual's power output; direct measurement of power output requires the use of a force plate. Two equations are primarily used and suggested to provide accurate predictions of power output: the Lewis formula and the Sayers formula (Harman *et al*., 1991; Sayers *et al*., 1999). The validity of the Lewis formula is imprecise for predictions of power output (Harman *et al.,* 1991). Thus, Sayers *et al.* (1999) proposed a new prediction formula using the SJ, resulting in a more accurate estimate of power output (Sayers *et al*., 1999).

Sayers Equation:

$$\text{Peak power (watts)} = 60.7 \cdot (\text{jump height [cm]}) + 45.3 \cdot (\text{body mass [kg.]}) - 2055$$

Brown and Weir (2001) developed a set of suggestions to help with field testing techniques and procedures and include, using the Sayers equation (1999), recording the VJ using the SJ. Three practice trials were performed before actual testing. With repeated measures, it is pertinent that use or non-use of arm thrusts be kept consistent and the knee angle at the start of motion must be kept the same with each repeated measure (Brown and Weir, 2001). This consistency allows more reliable results, as differences in SJ height can be attributed to muscle fatigue and not changes in technique of SJ.

Squat jump height has been shown to decrease following intermittent sports. More specifically, SJ showed a significant decrement in response to a soccer-specific protocol (Thorlund *et al.,* 2009). Furthermore, Houghton *et al.* (2011) found a significant ($p<0.05$) reduction in maximal SJ height following a simulated century batting protocol, which they attributed to muscle fatigue (Houghton *et al*., 2012).

MUSCLE ACTIVITY

Surface Electromyography

Surface electromyography (EMG) has been used to study fatigue in many previous studies (Bigland-Richie *et al.*, 1983; Moritani *et al.,* 1985). EMG has been useful in allowing comparisons of muscular activity among different sporting movements, and it is a valuable method of analyzing muscle activation (Rahnama *et al.*, 2006).

In previous studies on intermittent sports, a three-minute EMG protocol designed by Rahnama *et al*. (2006) (table II, page 42) has been used (Rahnama *et al.*, 2006; Christie and Cannon, 2012; Christie and Sheppard, 2012). A reference measure of muscular activity must be obtained prior to the activity or exercise being tested. This protocol can then be repeated post-protocol to assess the muscle activation changes, and allow the comparison of the muscle activation patterns for each player. This allows for an indication of the effect of an exercise or activity on muscle function. There is controversy in the literature with respect to changes in muscle activation associated with fatigue. Some studies have found that muscle activity increases with fatigue (Christie and Brown, 2012) while others have shown it decreases (Rahnama *et al*., 2006; Girard *et al*., 2008; Girard *et al*., 2010). With specific reference to cricket, studies on batsmen have found that hamstring muscle recruitment reduces in response to repeated sprints between the wickets (Christie and Sheppard, 2012). To the author’s knowledge no study has reported on muscle recruitment changes associated with fast bowling.

PERFORMANCE

While there are many definitions for performance of fast bowlers, all incorporate aspects of speed and accuracy. Ball release speed and accuracy, although differently assessed in previous studies, have been used to determine performance (Stretch and Goslin, 1987; Portus *et al*., 2000; Taliep *et al*., 2003). Performance is defined as the ability to maintain ball release speed and bowling accuracy throughout a bowling spell (Taliep *et al*., 2003).

Further success in higher standards of play for fast bowlers, is gained in sustained pace and accuracy (Lillee, 1977).

Ball Release Speed

Ball release speed is measured using a radar gun. The radar gun is either placed two-thirds of the way down the pitch, or behind the bowler, and is aimed away or towards the incoming bowler, at the point of ball release (Burnett *et al.,* 1995; Portus *et al.,* 2000; Taliep *et al*., 2000). Taliep *et al.* (2003) observed a significant difference in the ball release speed across a 12 over simulated bowling spell. The ball release speed significantly decreased after the 6th over, with overs 7 to 12 showing significantly slower ball release speeds than the initial 6 overs. In contrast, other studies have found no significant differences (Burnett *et al.,* 1995, Portus *et al.,* 2000, Duffield *et al.,* 2008). Portus *et al.* (2000) performed an analysis of variance with repeated measures of an 8 over bowling spell and revealed no significant changes in mean ball speed (F = 0.529, P = 0.595).

Accuracy

Accuracy provides a measurable indicator of performance for fast bowlers (Portus *et al.,* 2000). There has been a limited number of studies performed measuring bowling accuracy (Stretch and Goslin, 1987; Portus *et al.,* 2000; Taliep *et al.,* 2003). Previous studies have used different methods of scoring accuracy. Stretch and Goslin (1987) used pitch zoned targets, specifically designed to objectively assess the unknown skill of young cricketers for team selection. This method has been criticized, as it is suggested that pitch zoned targets will not fully asses performance of fast bowlers (Portus *et al.,* 2000). Portus *et al.* (2000) explain an in-swing bowler, for example, may hit a high-scoring zone on the pitch target (e.g. in line with the stumps), but in reality be bowling poorly because of the natural in-swing line of the delivery taking the ball down the leg side of the stumps. In addition to pitch zoned targets these workers used painted targets suspended in front of the stumps. The target was painted white on a black sheet. The sheet contained different scoring zones. This method allowed for better real-life match conditions to be assessed (Portus *et al.,* 2000). Accuracy is more specific to match conditions as the bowler will be required to control deviations through the air (Lillee, 1977).

CONCLUSION

In conclusion, although fast bowlers have a high injury incidence in the lower limb musculature, very little research has looked at changes in muscle function in response to fast bowling spells. Further, no studies have looked at changes in muscle recruitment over time in these players. Linking these musculoskeletal changes with perceptual responses and performance parameters will enhance our understanding of the demands placed on these players and provide areas for further research and intervention.

CHAPTER III

METHODOLOGY

INTRODUCTION

As there are few data aimed at investigating muscle fatigue during cricket, and, more specifically, in fast bowlers, the focus of this study was on fast bowlers. While the importance of the upper body and spinal kinematics are acknowledged, the main focus of this study was on the lower limb musculature and, more specifically, the quadriceps and hamstring muscle groups. The reason for this is that cricket injury surveillance data indicate a high percentage of injuries occurring in the lower limbs, yet the quantification of these demands has not been established. As a result of the repeated bouts of acceleration and deceleration during the run up and delivery in fast bowling, placing stress on the players' lower limb musculature, this was the primary focus of the investigation. Perception and performance of players is also recognized to hold a great deal of importance in the game of cricket. This investigation incorporated the muscular, perceptual and performance parameters of players over a simulated bowling spell.

PLAYER SELECTION

After explaining the nature of the investigation, and interest was expressed, fast bowlers' details were obtained from team captains. The players were then contacted and the nature of the study explained to them, following which players were invited to volunteer for the investigation. Many of the players explained the study to team mates, who became interested in taking part. If the players met all the inclusion criteria, they were then selected to perform in the investigation.

Inclusion Criteria

Only male fast bowlers were selected for the sample to be tested; players were required to bowl speeds of 100km.h^{-1} or higher. However, this was insured by measuring the ball release speed of players before testing took place. Players were required to be opening bowlers, or less preferably first change bowlers (3rd and 4th bowlers). Only players with no history of recent injury or illness performed in the study.

ETHICAL CONSIDERATIONS

Informed Consent

All players were informed, both verbally and in writing, of the procedures before testing. This included all the requirements during testing, equipment to be used, as well as the risks and potential benefits of the study. The study was approved by the Ethics Committee of the Human Kinetics and Ergonomics Department of Rhodes University, Grahamstown, South Africa (Appendix A, page 121). Voluntary, written consent was given by all players without any pressure from captains, coaches or other team members (Appendix A, page 122).

Anonymity of Results

A coding system was used during testing procedures in order to protect the identity of each player. Names were recorded on the data collection sheet only as a means of keeping track of participants and were only known to the tester (Appendix A, Page 122). Players were assured that information would be used for research purposes only.

RESEARCH DESIGN

A pre-test-post-test design was employed to measure muscle activation and functional strength changes of fast bowlers as the result of an eight over bowling spell. A repeated measures design was used to assess changes in perceptual and performance responses with time (Figure 1).

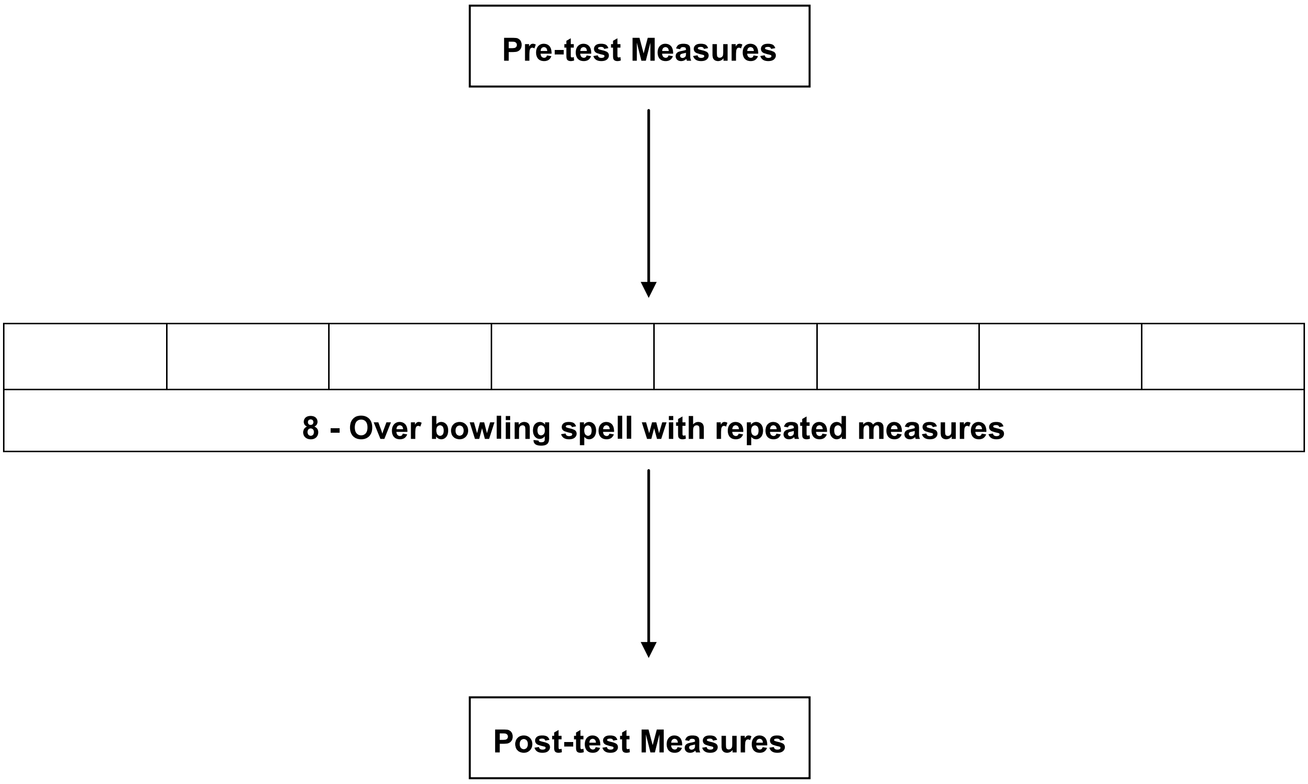


Figure 1: Experimental Design.

The dependent variables of interest were muscle activity, functional strength and power output changes, as well as perceived local muscle effort and discomfort. Performance measures were speed and accuracy of bowling. The independent variable was the eight over fast bowling spell.

The fast bowling protocol

Time motion analyses made it possible to accurately replicate real match play in a laboratory-based setting. The number of overs bowled for fast bowlers was between four and eight overs consecutively. Therefore an eight-over protocol was used as this would identify a ‘worst case scenario’. Time motion analysis data were recorded from one-day internationals matches during 2010/2011 season, including South Africa, West Indies, India, and Australia. Recent time motion analysis had been performed on ODIs (Christie and Sheppard, 2011), but not specifically for fast bowlers. In this investigation the times between deliveries were recorded from fast bowlers only.

It was discovered that each player was allowed 39 seconds per delivery (Table II). The completion of each over, which took 3 minutes 54 seconds, complied with the international cricket standards of 4 minutes per over. Following the over, there was a change-over of 1 minute 20 seconds; this was done to simulate the real match conditions. Bowlers walked slowly during this period, simulating real match play change-over. On completion of the change over, intermittent fielding drills were performed to simulate match conditions (Burnett *et al*., 1995). This took place for 3 minutes and 54 seconds. Fielding drills involved players walking in with the bowler, and fielding a total of one ball which was performed at random. The 1 minute 20 seconds change-over was once again allowed, as the players got ready to perform the next over. A step by step process to each over and player was taken, which was accurately repeated throughout the protocol (Table II). This work-bout was created to simulate a real match as accurately as possible, for an eight over bowling spell.

Table II: Work-bout protocol for each over

Steps	**Time (min:s)**	**During (min:s)**
Delivery 1	00:00	0.39
Delivery 2	00:39	0.39
Delivery 3	01:17	0.39
Delivery 4	01:59	0.39
Delivery 5	02:34	0.39
Delivery 6	03:13	0.39
Change-over	03:54	01:20
Fielding Drills	05:14	03:13
Change-over	09:08	01:20
Start Next Over	10:28	End
Bowling Total		03:54
Rest Total		02:40
Fielding Drills		03:54

Pilot studies investigated the average run-up distance of fast bowlers at a university level; these data were then used to set a range in which fast bowlers were to set their run-up. The range was set in order to control and limit variability resulting from players' different run-up lengths. The range was determined to be 15m to 25m. Players were asked to create a run-up which was natural and within these ranges. Players were requested to bowl with the technique most natural and the technique used in real match play.

EQUIPMENT AND MEASURES

ANTHROPOMETRIC DATA

Body Mass

Body mass was recorded using a calibrated electronic scale (Toledo Model 8141, Washington, Ohio, USA) and was measured to the closest 0.01 kg. All players were instructed in an identical fashion; to stand in the middle of the platform. Shoes, socks, jewelry and items on the body adding additional weight were removed; all items in pockets were removed ensuring an accurate reading of the player’s body mass.

Stature

Stature was measured to the nearest millimetre (mm) using a Harpenden Stadiometer (Quinton Instrument, Washington, Seattle, USA). The players had to remove their shoes, stand upright facing forward. Stature was measured from the floor to the vertex in the mid-sagittal plane.

Skinfold Measurement

Skinfolds were measured using Harpenden Skinfold calipers (Quinton Instrument, Washington, Seattle, USA). Skinfolds were recorded at seven different locations, namely: abdominal, chest, medial calf, subscapular, suprailliac, thigh and triceps. All measures were taken on the right hand side of the body with the skinfold caliper placed 10mm away from the thumb and finger, perpendicular to the skinfold. This process was replicated several times as a retest to determine if measures were within a 3% error margin. Body density was calculated using an equation devised by Jackson and Pollock (1978) as follows:

BD= 1.11200000-0.00043499(sum of 7 skinfolds)+0.00000055(sum of 7 skinfolds)2-0.00028826(age)

Using the Siri equation it was possible to determine body fat percentage.

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 (Biometrics Ltd, DataLOG W4X 8, Cwmfelinfach, Gwent, UK). Muscle activation patterns could not be measured during the fast bowling movement, therefore pre- and post- activation changes were measured and compared to one another. This was done using a treadmill protocol.

Electrodes were placed at a set inter-electrode distance of 20 mm. The main focus was on the lower limb musculature, more specifically the quadriceps and hamstring muscle groups. Four muscles were selected due to proximity to the surface; these were vastus medialis (VM) and vastus lateralis (VL) to determine the quadriceps muscle activation, as well as biceps femoris (BF) and semitendinosus (ST) to determine hamstring activation. The areas where electrodes were to be placed were shaved and cleaned with alcohol swabs. Once dry, the electrodes were attached to the surface of the skin, directly over the muscle belly and muscular activity was observed (Figures 2 and 3). Electrode placement is very important, therefore a guide was used for each player: Electrodes for biceps femoris and semitendinosus were placed 50% of the distance from the ischial tuberosity to the medial and lateral femoral epicondyles, respectively (Figure 2). The electrode measuring the vastus medialis was positioned 20% of the distance from the medial joint line, from the knee to the anterior superior iliac spine (Figure 3). The electrode which measured vastus lateralis was positioned at the midpoint between the head of the greater trochanter and the lateral femoral epicondyle (Figure 3). Four analogue channels were thus used to measure muscle activity, and one digital channel, which connected to a neutral electrode, was placed on an uninvolved muscle in order to minimize electrical impedance. The electrodes were kept on during the protocol, to ensure that the electrodes were in the same place pre- and post- protocol.

Figure 2: Diagrammatic representation of electrode placement for the hamstring musculature, semitendinosus on the left, and biceps femoris on the right (Taken form 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

(Taken from Muscle Tester Mega ME6000P16, Mega Electronics Ltd, Finland).

All information regarding muscle activity was transferred to a laptop via infrared telemetry for storage and data analysis.

EMG Normalisation Protocol

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). This was then repeated following the cricket-specific protocol. The protocol developed by Rahnama *et al*. (2006) assessed lower limb muscular fatigue specific to an intermittent soccer activity, and has more recently been used in rugby (Christie and Brown, 2009;Christie and Cannon, 2012), and cricket (Christie and Sheppard, 2012).

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 randomly walk, jog, stride and sprint on instruction, as the speeds altered. This took place on a Quinton 611 incremental treadmill and replicated speed ranges typically employed by bowlers during a cricket match.

To analyze the raw EMG a data reduction tool, Data Analysis Version 3.4, was used. This tool was developed within the Department of Human Kinetics and Ergonomics Department at Rhodes University. The raw EMG data had to be processed in order to understand the muscle activity. The first step involved the raw data signal being filtered to eliminate the hum. The amount of EMG activity was then identified as the area under the curve for EMG (μV) over time (seconds); The RMS of the EMG data were separated into the four speed categories (6, 12, 15 and 21 km.h^{-1}) which allowed RMS values pre- versus post-protocol to be compared easily (Table III). The units used to interpret the EMG data were arbitrary units (a.u). Extreme outliers were excluded from the data range.

MUSCLE STRENGTH

Squat Jump

Field tests allow for quick and non-invasive measurements of muscle power, with minimal use of equipment (Brown and Weir, 2001). Muscle power output was measured using VJ, more specifically the SJ. SJ requires players to start in a semi-squat position: knee angle at 115°, and feet 12.5- 25cm laterally separated. Players were then instructed to jump as high as possible in one explosive movement, and touch the VJ board at the highest point; arm thrusts were allowed. Technique for SJ remained constant throughout testing through observations by the primary researcher.

SJ was measured recorded pre- and post- protocol and following the EMG normalization protocol. Three practice trials were completed prior to recording test performance. Players were told when the starting position was obtained. Testing involved players performing three SJs, all of which were observed directly by the experimenter. SJs were only allowed if the technique adopted by players was correct. The technique was assessed by the same researcher and research assistant for each player. The mean of the players' SJ performances was used in assessments with the prediction equations.

The Sayers equation was used to predict muscle power output. Sayers *et al.* (1999) proposed a prediction formula using the SJ, which results in a more accurate estimate of power output than previous equations (Sayers *et al*,. 1999).

Sayers Equation:

$$\text{Peak power (watts)} = 60.7 \cdot (\text{jump height [cm]}) + 45.3 \cdot (\text{body mass [kg.]}) - 2055$$

Jump Meter

Figure 4: Player performing a SJ using the electrical jump meter.

SJ was recorded using an electrical touch-sensitive jump meter device (Jump Meter, Takei Kiki Kogyo Co. ltd, Japan), which automatically recorded jump height when touched, and displayed it on the jump meter screen. The VJ board was adjusted to fit each player. The player stood adjacent the VJ board, fully extending their arm upwards and the VJ board was then moved up or down according to the reach height of the player.

PERCEPTUAL MEASURES

Rating of Perceived Exertion (RPE)

Borg's (1982) Ratings of Perceived Exertion Scale was used to asses perceived exertion of players. “Local” RPE, representing effort perceptions of selected muscular groups, was used to provide an indication of perceived lower limb discomfort (quadriceps and hamstrings). The Borg scale contains values ranging from 6-20, with 6 representing the smallest amount of strain and 20 representing the highest level of strain exhaustion. These value ranges were explained to the players before the testing protocol took place (Appendix B, page 132). Local RPE was obtained and recorded at the completion of each over.

The Body Discomfort Map and Scale

Corlett and Bishop's (1976) body discomfort and rating scale was used to measure any pain or discomfort experienced by players, and the strain placed on the musculoskeletal system. Discomfort was rated on a scale from 1 to 10, with one representing the least discomfort and ten indicated maximal discomfort levels. Sites and discomfort were obtained and recorded. Players were requested to indicate any discomfort prior to the protocol, as a control measure. Players were then required to indicate discomfort (if any) at the end of each over. Anterior and posterior views of the body with 28 regions are shown on the body discomfort and rating scale (Appendix B, page 133). This allows for accurate indications of the site or source of discomfort.

PERFORMANCE MEASURES

Ball Release Speed

A sports radar gun (SR 3600, Sports Radar Ltd, Florida, USA) was used to measure ball release speed. Ball release speed was measured and recorded after each delivery, for all eight overs, by the researcher and research assistant.

The sports radar gun is a microprocessor-based computing device that uses a low power doppler radar transceiver. The radar gun sends out a signal, which bounces off the cricket ball/player's hand and reflects back to the radar gun. A mixer provides the difference in frequencies from the original sent signal and the signal that has been returned from the cricket ball. The difference in signals is proportional to the speed of the object. The radar gun has a microprocessor which calculates the speed of the object is moving in km.hr^{-1}.

Figure 5: Radar gun placement; 10m behind the bowler.

To accurately calculate the speed of ball release and standardize the reliability, the radar gun was placed directly behind the bowler on a tripod stand, set on the same line as the target travel, ensuring the angle at which the radar gun was pointed was the same for each player. The radar gun was set up in the same position (10m behind the stumps) for each fast bowler. The gun was aimed in the same way, ten meters away to ensure the most accurate and consistent results.

Accuracy

A method developed by Portus *et al* (2000) was used, and an accuracy board was suspended behind the stumps (Figure 6). The target was made of a fabric, replicating the dimensions in previous studies. The target contained different scoring zones which were clearly marked by white boarders on the black fabric sheet (Figure 6).

The maximum scoring zone was in the position of the stumps (100 points), and the minimum scoring zone was furthest from the stumps (25 points). If the ball was not delivered into any scoring zones, no points were awarded. This method allowed for better real life match conditions to be assessed (Portus *et al.,* 2000). Accuracy is more specific to match conditions as the bowler will be required to control deviations through the air (Lillee, 1977).

The players were requested to bowl as accurately as possible, and accuracy was recorded by using the accuracy scoring zone points. Accuracy was measured after each delivery, for all eight overs by two researchers. The mean accuracy for each over calculated indicates performance differences throughout the protocol.

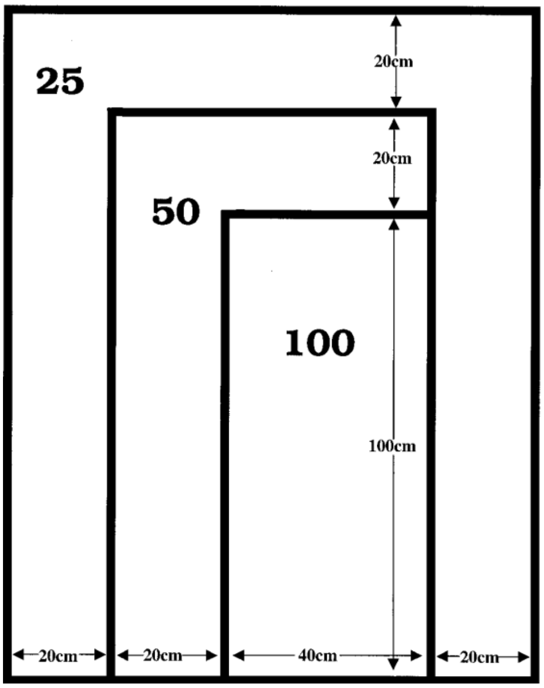


Figure 6: Dimensions and scoring zones of the accuracy target (Portus *et al*., 2000)

PROTOCOL TESTING SITE

High Performance Center In-door Pitch

Testing took place in The Kingswood High Performance Centre (HPC). The in-door pitch is fitted with a synthetic sports floor made by Fintrex (Johannesburg, South Africa). Fintrex specializes in the construction of sports flooring. The Kingswood HPC is fitted with a surface called Uniturf, which is an embossed sheet vinyl material, and is a specialized cricket material system. Within this centre there are cricket nets set up, which can be pulled out. Crease and pitch markings are displayed with different easily-identifiable colours on the surface. The bowler is also allowed more than enough space to perform each run-up.

ADDITIONAL EQUIPOMENT

Quinton 611 incremental Treadmill

To control the speed of running, the Quinton 611(Quinton, Washington, Seatle), an incremental treadmill, was used for the normalization protocol. This treadmill supports a variety of functions, including the implementation of various speeds and gradients. However, for the purpose of this study the treadmill was set at a level gradient and used speeds ranging from 5km.h^{-1} to 21km.h^{-1}.

Questionnaire

A physical activity screening questionnaire indicated past diseases, disorders or injuries, and highlighted any medication the player was currently taking, whether prescribed or self-medicated. It allowed insight into any medical history for each player. It also provided insight as to whether any of the players were smokers, and provided an exercise history for each individual (Appendix A, page 124).

PILOT TESTING

Prior to experimentation, extensive pilot studies were conducted to ensure the accuracy and validity of the laboratory-based (simulated) protocol developed. The pilot studies investigated the musculoskeletal and perceptual demands placed on fast bowlers during a simulated fast-bowling work-bout. Pilot testing was also used to familiarize the experimenter and players with the in-door cricket pitch, jump meter and electromyography (EMG) equipment.

EXPERIMENTAL PROCEDURES

Players were involved in two testing sessions. The first session involved habituation and the collection of selected anthropometric, morphological and demographic data of the players. The remaining session represented the experimental condition. Muscle activity testing and functional strength testing took place within the Department of Human Kinetics and Ergonomics (HKE) at Rhodes University, Grahamstown, South Africa. The work-bout protocol took place at Kingswood College in the High Performance Center, which is located near to the Department of HKE.

SESSION I: INTRODUCTION AND BASELINE DATA COLLECTION

The purpose of this testing session was to explain in detail the purpose and objectives of the study, sign informed consent (Appendix A, page 122), and collect basic demographic, morphological and anthropometric data (body fat percentage, height and mass). In addition, ball release speed was measured as a baseline and to allow comparisons to be made between similar studies. Players were not forced to sign the consent form, or placed under any obligation to perform the study, and players were informed that they could choose to leave the study at any time. Equipment being used, and the scoring method, was explained in detail to each player. The rating of perceived exertion (RPE) and body discomfort scales were then adequately explained to each player (Appendix B, page 144). Players were then driven to the Kingswood High Performance center and habituated to the in-door pitch and the protocol. After this the players were driven to the Human Kinetics and Ergonomics Department and habituated to the treadmill and the functional strength tests (Jump Meter). If the familiarization was not completed during the first session, another session was scheduled.

SESSION II: EXPERIMENTAL CONDITION

Players were requested to not participate in strenuous exercise, take any unnecessary medication, or consume alcohol 24 hours prior to testing, and not to eat within two hours of the testing sessions. The simulated work-bout took place on an indoor pitch at the Kingswood HPC, while the muscle activity measures and functional strength tests took place in the laboratory, which is close to the field of play.

Players were required to participate in a cricket-specific warm up, including stretching and any other warm-up routine they might require, minimizing the risks of injury during the protocol.

EMG electrodes were then attached at shaved and cleaned areas; the area was wiped with an alcohol swab and left to dry, to ensure good connectivity. EMG electrodes were attached to the dominant lower limb of the player, in the direction of the muscle fibers, positioned in such a way as to limit interference from surrounding muscles and ensure good connectivity from the muscles concerned. One neutral electrode was attached to the player’s bicep, which is an uninvolved muscle and thus eliminated electrical impedance. Electrodes were taped down and remained attached for the duration of the study. Players were taken to the treadmill area and a warm-up was performed, as well as any other stretches the player usually did before starting a bowling spell. The normalization protocol used to assess the muscular activity was once again briefly explained, as well as speeds and durations at each speed discussed. The bowler then did the normalization protocol followed by the vertical jump test. On completion of the pre-protocol tests players were driven to the Kingswood HPC. The Kingswood HPC is near to the Human Kinetics and Ergonomics Department. On arrival at the HPC the players were allowed to perform any additional stretches aend mark out a run-up which was most comfortable. The testing area had been set up before the arrival of each subject, including the radar gun, accuracy board and stumps placed at each crease.

The ‘local’ RPE and body discomfort scales were briefly explained again, as well as the performance measures, and scoring zones associated with each. Once players felt ready to start, the eight over (48 balls) work-bout commenced. On the completion of each over the player was asked to indicate perceived local RPE, and indicate, and score, any body discomfort. Bowling speed and accuracy were recorded following each delivery by the researchers (Appendix B, page 136). On completion of the work-bout protocol, players were driven back to the Department without any delays, and the post- measures of muscular activity and functional strength tests were repeated. Each player was asked to complete a cool- down stretching session to limit the amount of discomfort experienced following the experimentation process. The stretching involved static stretches of both lower and upper limbs, and in addition to this players were asked to perform any other stretches they may have felt were needed.

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. Dependent T-Tests were performed on muscle activity data recorded pre- and post-protocol. One-way Analyses of Variance (ANOVA) with repeated measures were then used to identify statistically significant changes in perceptual measures and performance measures over time. 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

BASELINE MEASURES

Table IV: Mean selected player characteristics (± standard deviation and coefficient of variation).

	Mean	**SD**	**CV (%)**
Age (yrs)	21.62	1.39	-
Stature (cm)	182.3	7.06	-
Mass (kg)	79.51	11.38	-
BMI (kg.$(m^2)^{-1}$)	22.99	5.36	23
Body fat (%)	14.05	4.64	33

A total of 26 fast bowlers, with a mean age of 21.62 (±1.39) years agreed to participate in the study (Table IV). The baseline data, excluding body fat percentage, showed a low variability. Thus, the sample used had similar demographic, morphological and anthropometric characteristics (Table IV).

ENVIRONMENTAL CONDITIONS

Testing took place in a laboratory setting to avoid the influence of extraneous environmental factors. Further, ambient temperatures were recorded on the days of testing. The mean temperature was 22.38 (3.18)°C and testing took place in an environmental window of 17°C to 28°C. Testing did not take place on days with extreme temperatures.

BIOPHYSICAL PARAMETERS

ELECTROMYOGRAPHY

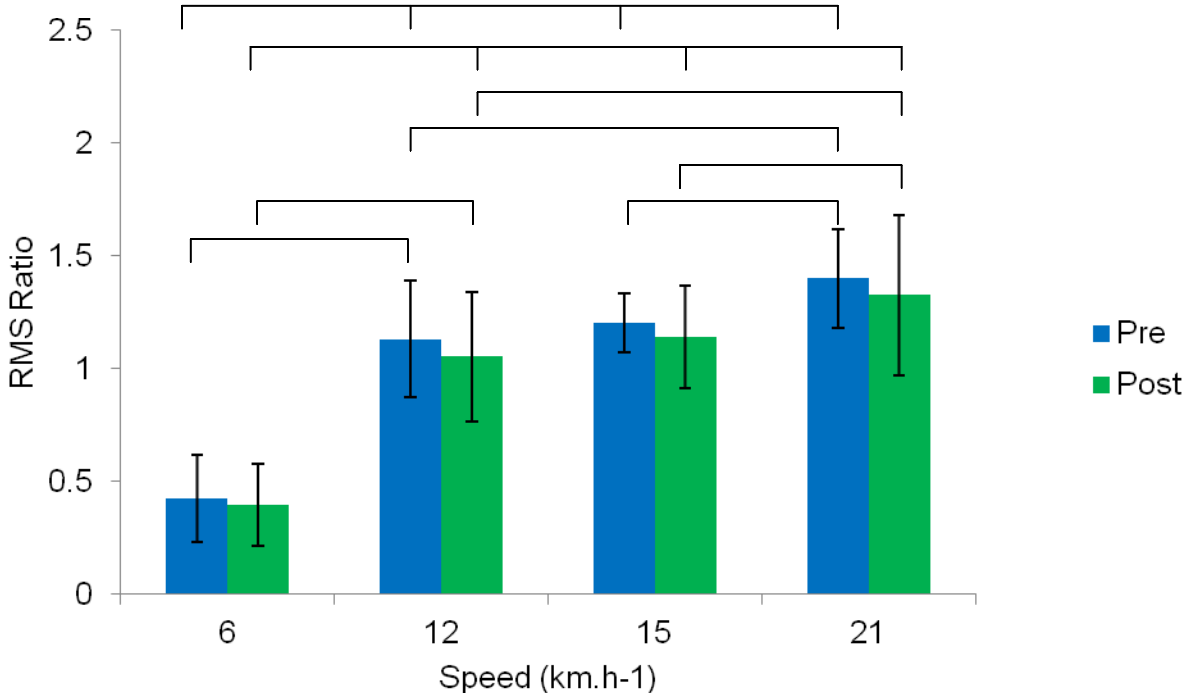
Muscle activity increased with each increment in treadmill speed (Table V). The trend was for a decrease in muscle activity following the bowling spell (Table V). These decreases were, however, not significant. Muscle activation was observed to be similar between muscles, both in the quadriceps and hamstring muscle groups.

Table V: A comparison of the pre and post RMS values at each speed during the EMG protocol for the quadriceps and hamstring musculature.

Condition	**Speed**	**Muscle RMS**			
	(km.h^{-1})	**VM**	**VL**	**ST**	**BF**
Pre	**6**	0.43	0.42	0.42	0.42
	12	1.13	1.09	1.01	1.04
	15	1.2	1.24	1.18	1.18
	21	1.4	1.4	1.56	1.52
Post	**6**	0.4	0.37	0.45	0.41
	12	1.05	1.08	1.01	1
	15	1.14	1.14	1.13	1.13
	21	1.33	1.34	1.29	1.45

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

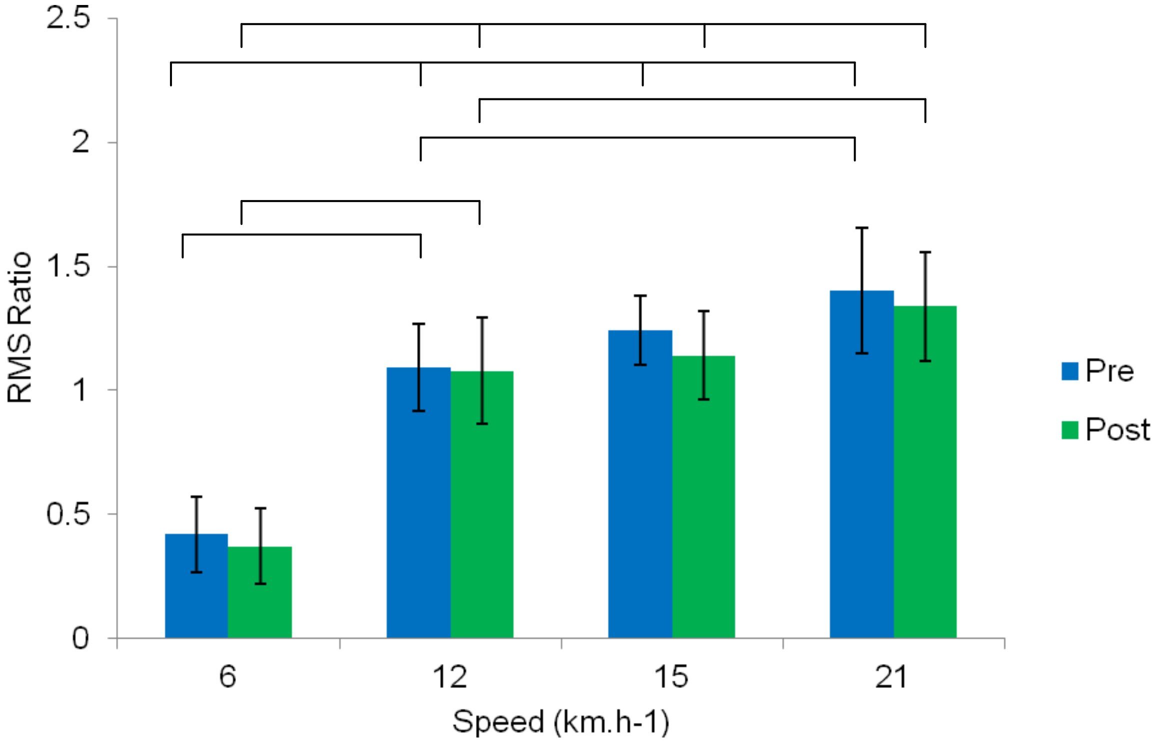
Quadriceps Musculature



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

Figure 7: Mean (±SD) RMS ratio (referenced to all speeds prior to each condition) within the VM muscle pre- and post-protocol.

VM muscle activation increased significantly ($p<0.05$) during the pre-normalisation and post-protocol trials between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h^{-1}, 12km.h^{-1} - 21km.h^{-1}, and 15km.h^{-1} - 21km.h^{-1}. Although muscle activation of the VM increased significantly with increasing treadmill running speed (Figure 7), there were no significant changes in VM muscle activation, following the eight over bowling spell at all treadmill speeds (6-21km.h^{-1}). There was, however, a trend for a decrease in VM activation, particularly at the three faster speeds.



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

Figure 8: Mean (±SD) RMS ratio muscle activation within the VL muscle pre- and post-protocol.

Muscle activation increased significantly ($p<0.05$) in the VL during the pre-normalisation protocol between testing speeds 6km.h^{-1} - 12km.h^{-1}, and 12km.h^{-1} - 21km.h^{-1}, with the slowest speed (6km.h^{-1}) being significantly slower than all other testing speeds (Figure 8). During the post-protocol testing, VL activation increased significantly ($p<0.05$) between 6km.h^{-1} - 12km.h^{-1} and 12km.h^{-1} - 21km.h^{-1}, with the slowest speed (6km.h^{-1}) being significantly slower than all other testing speeds. There were no significant changes in VL activation, following the eight over bowling spell at all treadmill speeds (6-21km.h^{-1}). There was, however, a trend for a decrease in VL activation, particularly at the faster speeds (15 km.h^{-1} and 21 km.h^{-1}).

Hamstring Musculature

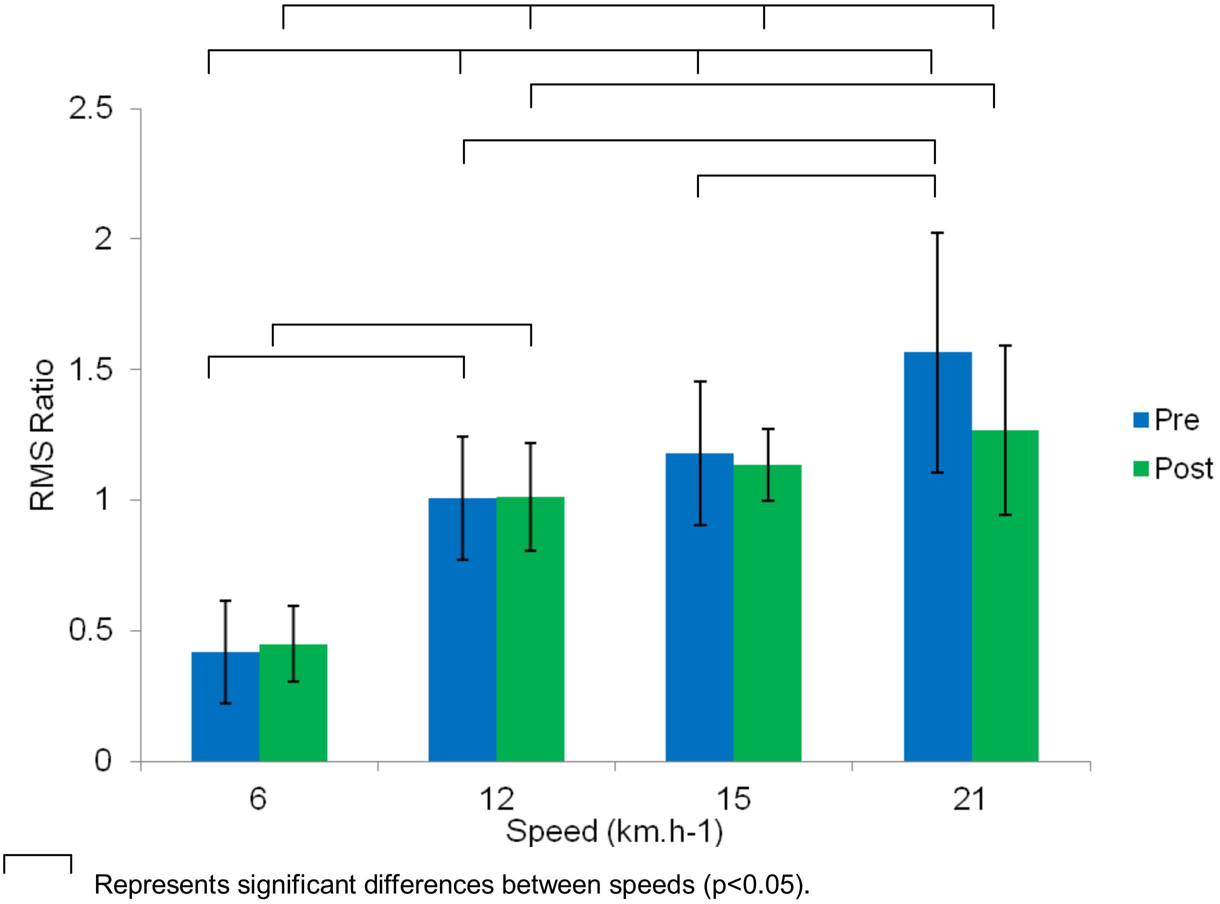
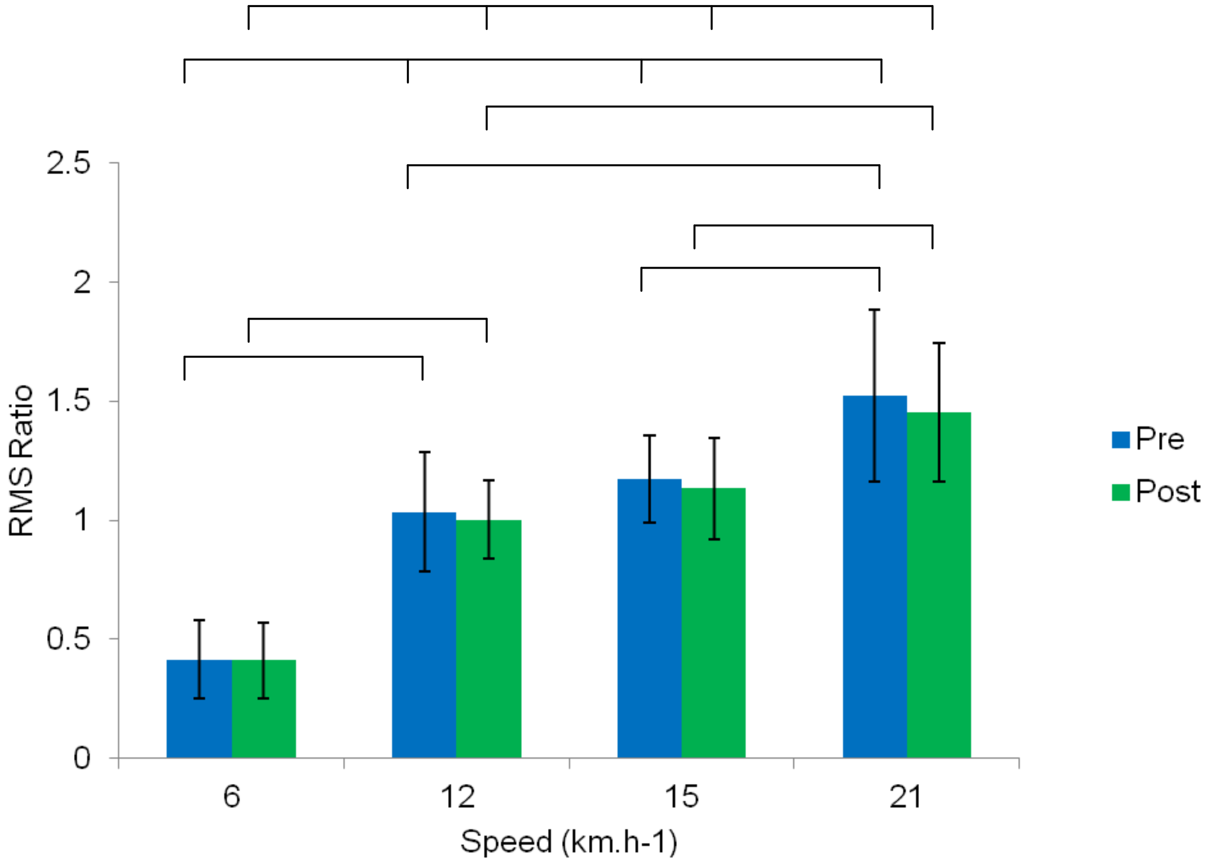


Figure 9: The mean (±SD) RMS ratio muscle activation within the ST muscle pre- and post-protocol.

ST activation increased significantly ($p<0.05$) during the pre-normalisation protocol between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h^{-1}, 12km.h^{-1} - 21km.h^{-1}, and 15km.h^{-1} - 21km.h^{-1} (Figure 9). During the post-protocol testing, significant ($p<0.05$) increases in muscle activation were observed between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h^{-1} and 12km.h^{-1} - 21km.h^{-1} (Figure 9). There were no significant changes in ST activation, following the eight over bowling spell at all treadmill speeds (6-21km.h^{-1}). There was, however, a trend for a decrease in ST activation, particularly at the fastest speed (Figure 9).



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

Figure 10: Mean (±SD) RMS ratio muscle activation within the BF muscle pre- and post-protocol.

BF muscle activation increased significantly ($p<0.05$) during the pre-normalisation and post-protocol between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h^{-1}, 12km.h^{-1} - 21km.h^{-1}, and 15km.h^{-1} - 21km.h^{-1} (Figure 10), similarly to the VM muscle activation patterns (Figure 7). There were no significant decreases in BF activation, following the eight over bowling spell at all treadmill speeds (6-21km.h^{-1}). There was, however, a trend for a decrease in BF activation, particularly at the faster speeds (Figure 10).

Table VI: Percentage (%) change in muscle activation at different speeds comparing pre- and post- protocol.

	Speed (km.h^{-1})			
	6	**12**	**15**	**21**
VM	-7.0%	-6.9%	-5.2%	-5.6%
VL	-11.4%	-1.2%	-8.0%	-4.5%
ST	7.7%	0.0%	-4.0%	-16.9%
BF	-1.0%	-3.1%	-3.4%	-4.7%
Mean (± SD)	-2.9 (± 5) %	-3 (± 3) %	-5 (± 5) %	-8 (± 6) %

Where:

🟥 Decrease in (%) muscle activation

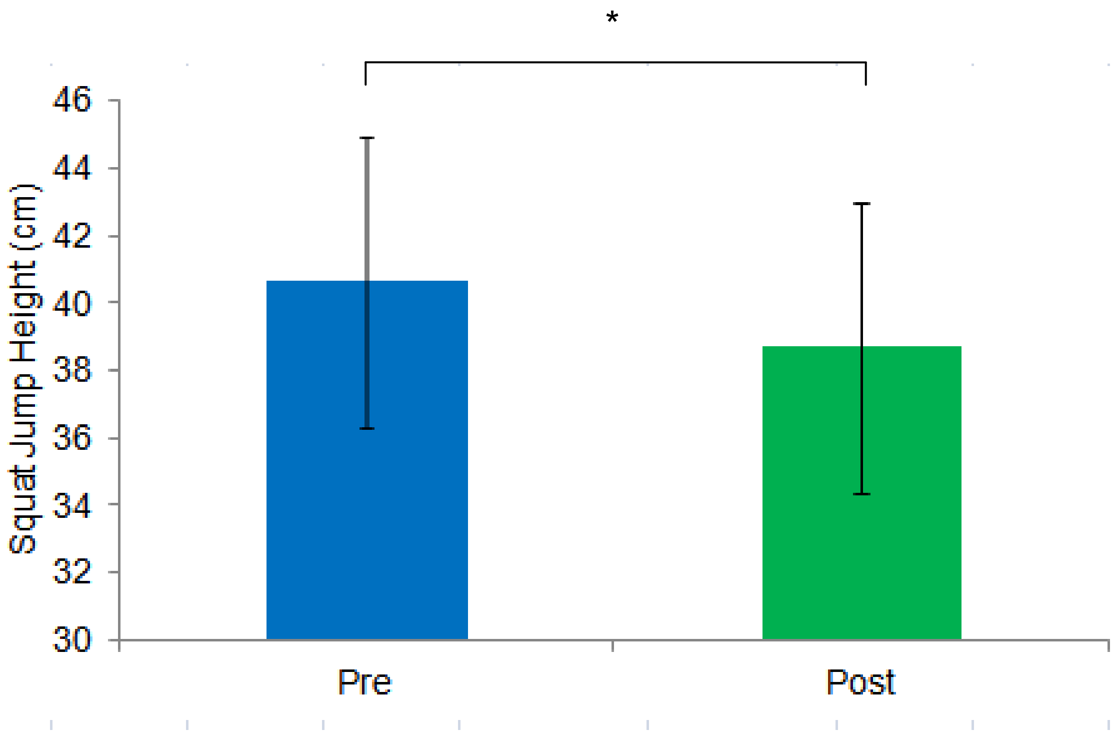
🟩 Increase, or no change in (%) muscle activation.

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

The percentage decrease in muscle activations were observed to be between 1.2 and 11.4% for the quadriceps muscles (VM and VL). The changes in muscle activity for the ST ranged from an increase of 7.7 % to a decrease of 16.9% (Table VI). The highest decreases in muscle activity for the quadriceps muscle group occurred at the lowest testing speed. The highest decreases in muscle activity for the hamstrings, and specifically the ST, occurred at the highest testing speeds. The largest mean percentage decrease in muscle activity was observed at the highest testing speed, and in the ST muscle which showed a decrease of 16.9% (Table VI). Overall, muscle activity decreases were observed to increase as a function of speed.

FUNCTIONAL STRENGTH

Squat Jump

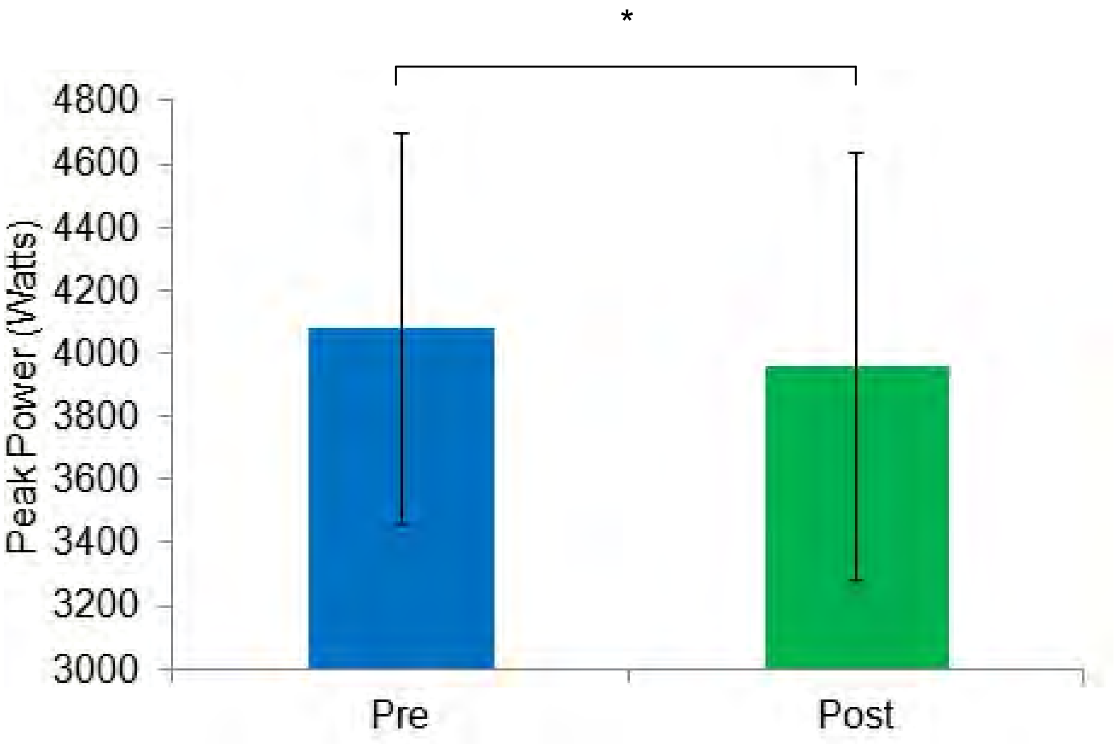


* Represents significant differences in vertical jump between pre- and post-protocol tests ($p<0.05$)

Figure 11: The mean (±SD) squat jump pre- and post-protocol

There was a significant ($p<0.05$) drop in vertical jump height following the 8-over protocol. The mean jump height pre-protocol was 40.63 (±4.3) cm and the mean jump height post-protocol was 38.68 (±5.66) cm; a 1.95 cm change.

Power Output



* Represents significant differences in vertical jump between pre- and post-protocol tests (p<0.05)

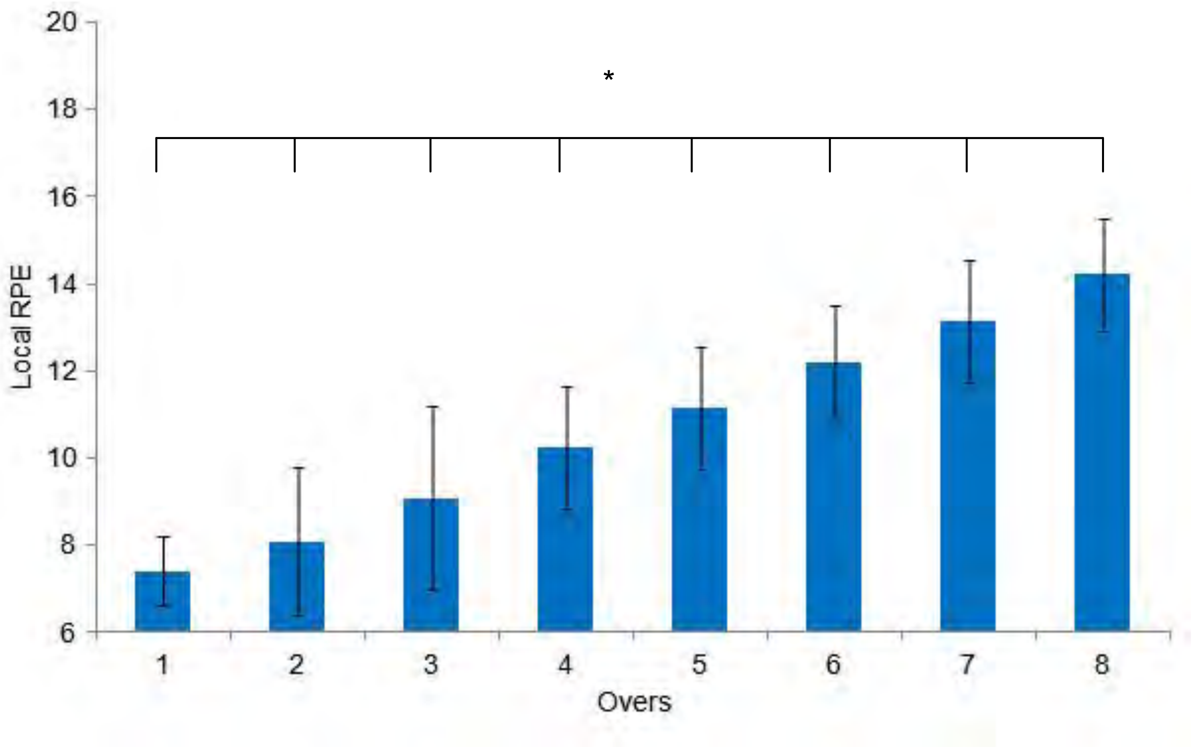
Figure 12: Mean (±SD) power output predictions pre- and post-protocol

There were significant ($p<0.05$) decreases in peak power following the simulated eight over bowling spell (Figure 12). The mean peak power pre- protocol was 4078.5 (±618.4) watts and the mean peak power post-protocol was 3960.2 (±677) watts; a 118.3 watt change.

PERCEPTUAL PARAMETERS

RATING OF PERCEIVED EXERTION (RPE)

'Local' RPE



*Represents significant differences over time ($p<0.05$) in local RPE

Figure 13: Mean (±SD) 'local' ratings of perceived exertion (RPE) recorded on the completion of each over.

There were significant ($p<0.05$) increases in 'local' RPE from the first over onwards, with each subsequent over being significantly ($p<0.05$) lower than the previous (Figure 13). Thus, local perceptions of effort increased as a function of bowling duration. The lowest RPE rating by players was in the first over with a perceived rating of 7.4 ± 0.8, while the last over was perceived as the most taxing, with a perceived rating of 14.2 ±1.3 (Figure 13).

Body Discomfort

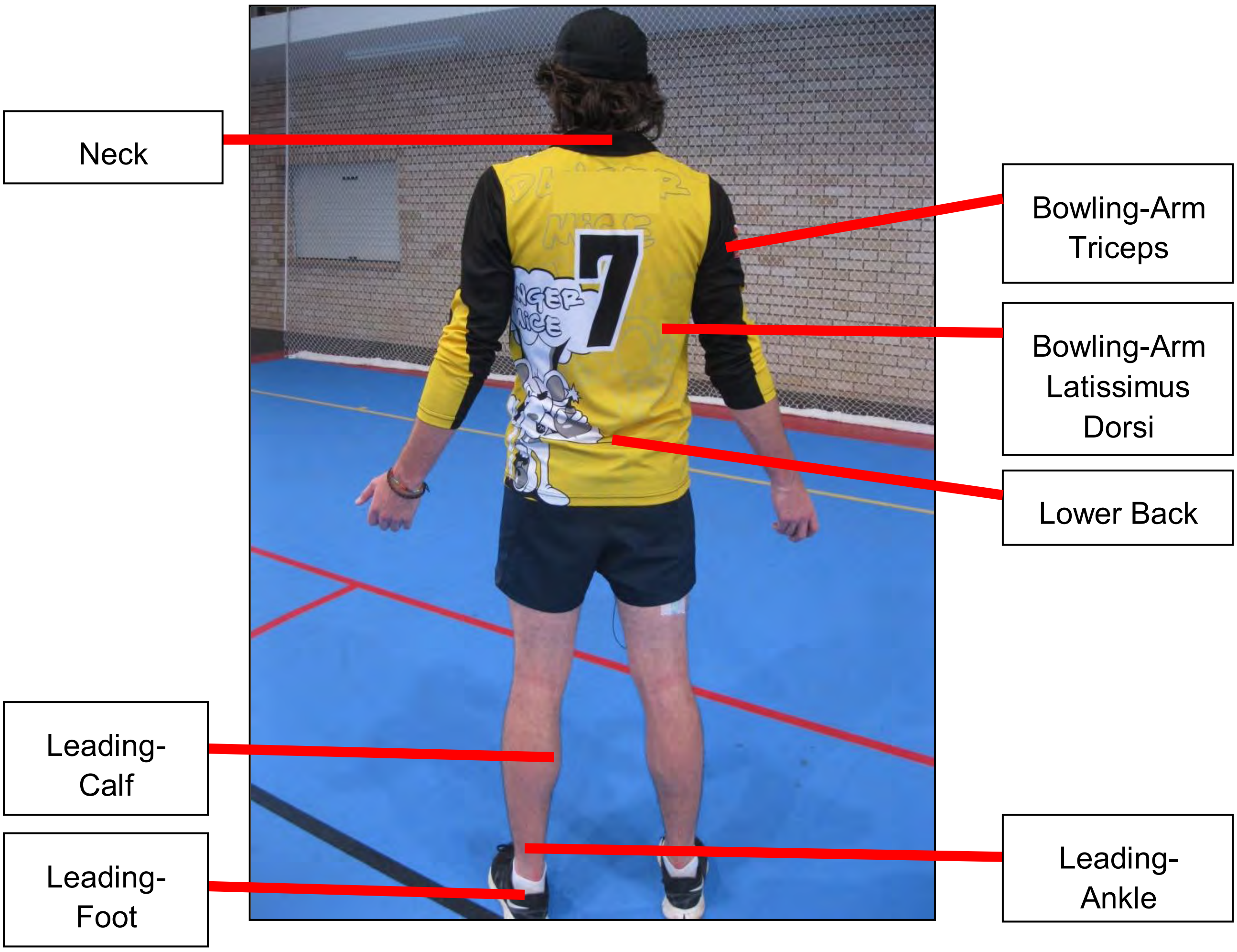


Figure 14: Posterior perceived body discomfort sites.

Most of the discomfort experienced by the bowlers was to the posterior aspect of the body and isolated mainly to the bowling arm side and the lower limb area of the leading leg (Figure 14).

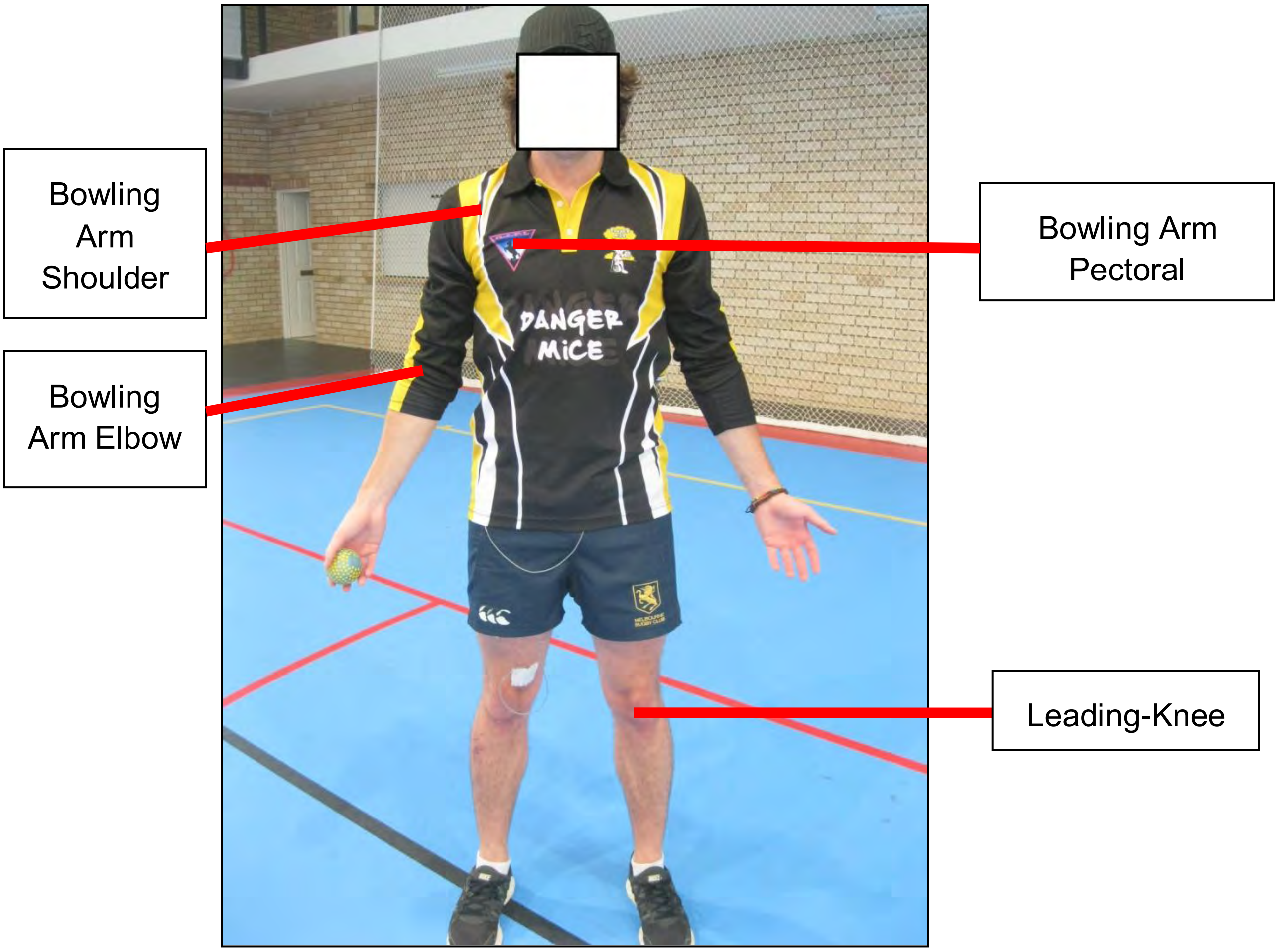


Figure 15: Anterior perceived body discomfort sites.

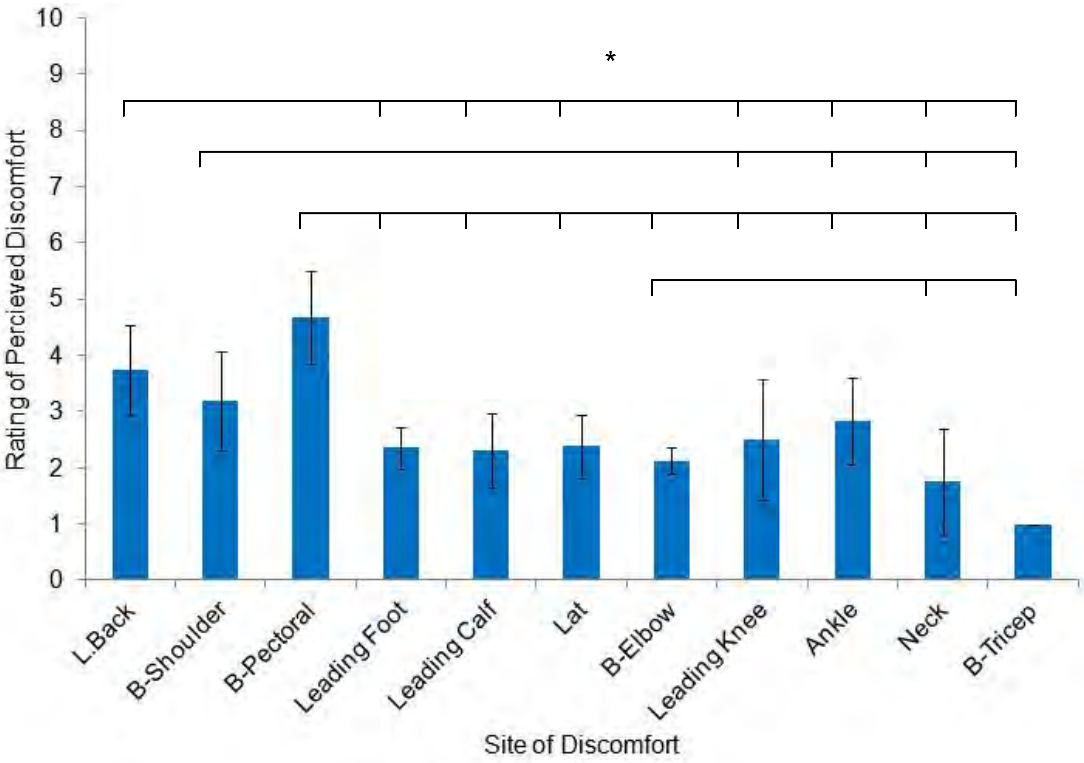
Anterior discomfort was also isolated to the bowling arm and lower limb of the leading/non-dominant leg (Figure 15). Areas of discomfort were shown to be posterior, while the pectoral, shoulder, leading knee and bowling elbow were the only anterior areas of discomfort experienced by players.

Table VII: A comparison of the number of players (%) perceiving discomfort at each over, and locations of these discomforts.

	Bowling Spell							
Region	**Over 1**	**Over 2**	**Over 3**	**Over 4**	**Over 5**	**Over 6**	**Over 7**	**Over 8**
L.Back	12%	12%	27%	31%	38%	46%	50%	50%
B-Shoulder	15%	15%	23%	23%	23%	23%	35%	31%
B-Pectoral	15%	19%	23%	23%	27%	23%	23%	23%
Leading Foot		4%	8%	12%	19%	27%	15%	19%
Leading Calf		4%	8%	4%	12%	8%	12%	8%
B-Lat		4%	8%	12%	8%	27%	15%	19%
B-Elbow	8%	8%	4%	4%	4%	4%	4%	4%
Leading Knee			4%	4%			8%	8%
Ankle						8%	4%	8%
Neck			4%	4%	4%			
B-Triceps	4%	4%	4%					

Where: L.Back = Lower Back, B-Lat = Latissumus Dorsi, B-Shoulder = Bowling Shoulder, B-Pectoral = Bowling Pectoral, B-Elbow = Bowling Elbow, B-Tricep = Bowling Tricep.

Body discomfort ratings for the pectorals, shoulder, elbow, triceps and latissimus dorsi all occurred on the bowler’s dominant side (bowling arm side). Upper limb and bowling arm pectoral discomfort was experienced from the onset of the bowling spell (Table VII). The discomfort was more frequently reported in the dominant pectoralis muscle of players as the bowling spell progressed. The same was true for the dominant shoulder. The elbow discomfort reduced in number over time, while latissimus dorsi discomfort became prevalent after the second over with more reports of discomfort over time. The lower back (LB) region gained the highest incidence of body discomfort, with 50% of players experiencing LB discomfort nearer the end of the protocol. Reports of discomfort in the leading ankle region (gastrocnemius/soleus) and leading knee area became more prevalent in the latter three overs (Table VII). No discomfort was reported in the quadriceps or hamstring muscles of players, which corresponds to muscle activity results which showed no significant change in the lower extremities (Figures 7,8,9, and 10).



*Represents significant differences ($p<0.05$) in players perceived body discomfort between areas.

Where: L.Back = Lower Back, Lat = Bowling side Latissumus Dorsi, B-Shoulder = Bowling Shoulder, B-Pectoral = Bowling Pectoral, B-Elbow = Bowling Elbow.

Figure 16: Mean (±SD) perceived intensities of body discomfort.

The highest rating of discomfort came from the pectoral musculature of the bowling arm, followed by the lower back and shoulder (Figure 16). The dominant pectoral muscle was perceived to have significantly ($p<0.05$) more discomfort than all but two discomfort sites (lower back and bowling shoulder). The lower back was also shown to have significantly ($p<0.05$) higher body discomfort ratings than the majority of the discomfort sites (Figure 16). Players perceived the bowling shoulder to be taking significantly ($p<0.05$) more strain than the leading knee, ankle, neck, and the dominant triceps. These three areas (lower back, bowling shoulder, and dominant pectoral) also showed the highest number of players experiencing discomfort (Table VII). It should be noted that lower back discomfort may have been perceived by more players; however the intensity relative to the dominant pectoral muscle was shown to be lower. Other significant ($p<0.05$) differences were observed between the bowling elbow, neck and dominant triceps; the perceived discomfort being greatest in the bowling elbow.

PERFORMANCE MEASURES

Accuracy

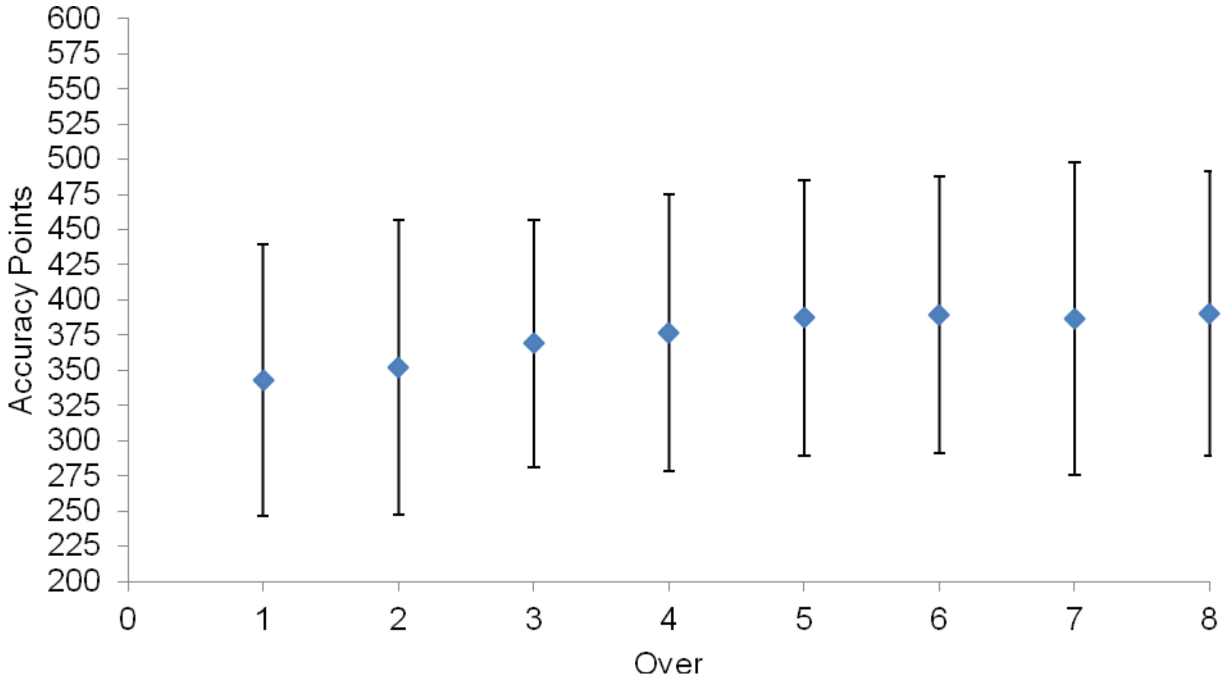
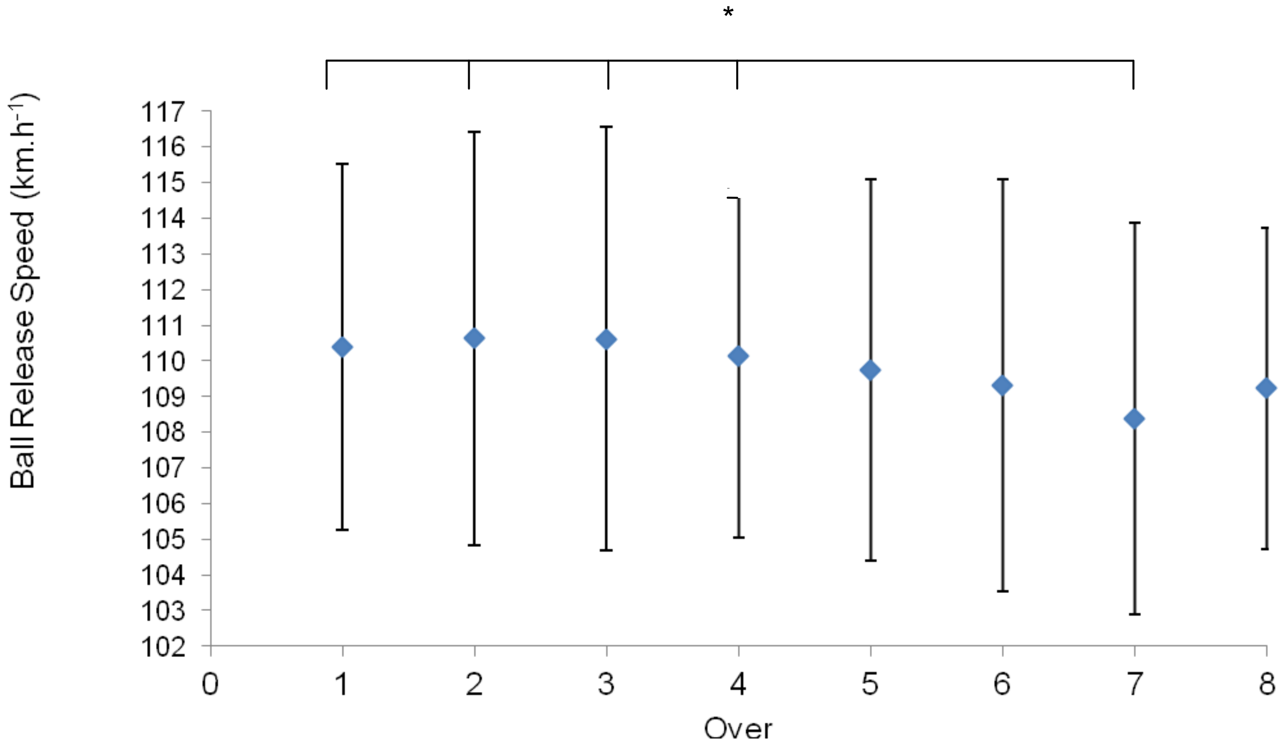


Figure 17: Mean (±SD) accuracy scores of players for each over.

There were large inter-individual differences in accuracy; this is shown by the high standard deviations (Figure 17). There were no significant changes in accuracy between overs. The highest score (a perfect score) a player would be able to obtain was 600 points. The highest scoring over for players, as a group, was in over eight (390.38±101.26 points), while the lowest scoring over was the first (347.27±96.322 points).

Ball Release Speed



*Represents significant differences ($p<0.05$) in ball release speed.

Figure 18: Mean (±SD) ball release speeds of players for each over.

Mean ball release speed ranged between 108.38 (± 5.48) km.h^{-1} during over seven (slowest over), and 110.63 (± 5.79) km.h^{-1} (fastest over) during over three, and remained fairly consistent throughout the eight over spell. The exception was over seven (108.38± 5.48 km.h^{-1}), when ball release speed decreased significantly ($p<0.05$) compared to overs one to four. Thereafter, ball release speed was restored with a mean of 109.23 (± 4.5) km.h^{-1} during the eighth over. There was a large inter-individual difference between players in the selected sample group. The fastest player bowled at a ball release speed of 117.5 (± 3.1) km.h^{-1}, while the slowest player in the sample group achieved a ball release speed of 101 (± 0.8) km.h^{-1}.

CORRELATIONS

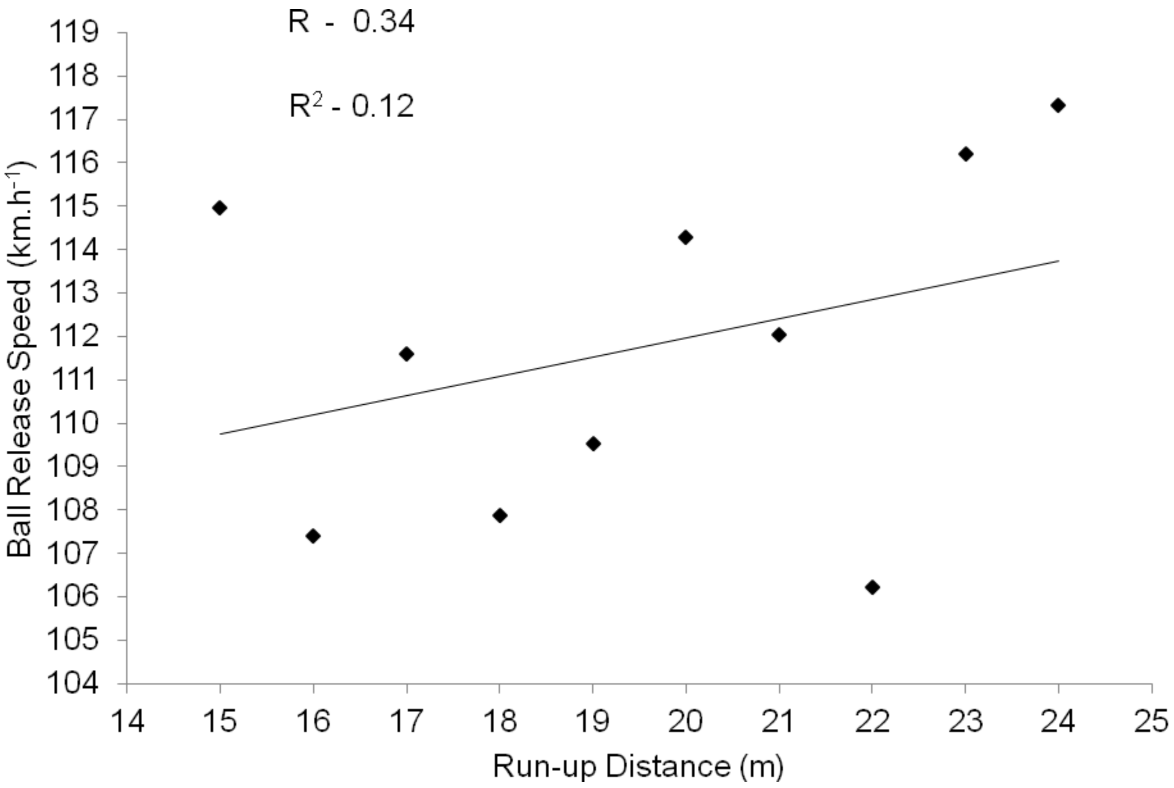


Figure 19: Correlation between run-up distance (m) and ball release speed.

There was a weak (R = 0.34) positive correlation between ball release speed and run-up distance (Figure 19). Ball release speed ranged from 106.23 km.h^{-1} at a run-up distance of 22m, to 117.34 km.h^{-1} at a run-up distance of 24m. There was a general trend for the longest run-up distances (23 and 24m) to have the fastest ball release speeds, except for a run-up distance of 15 m which had a ball release speed greater than run-up distances of 16m-22m. Interestingly, it was at 22m that the slowest ball release speed was recorded. This high variability between run-up distances and ball release speed resulted in a weak association (R^2 value of 0.12) between run-up distance and ball release speed.

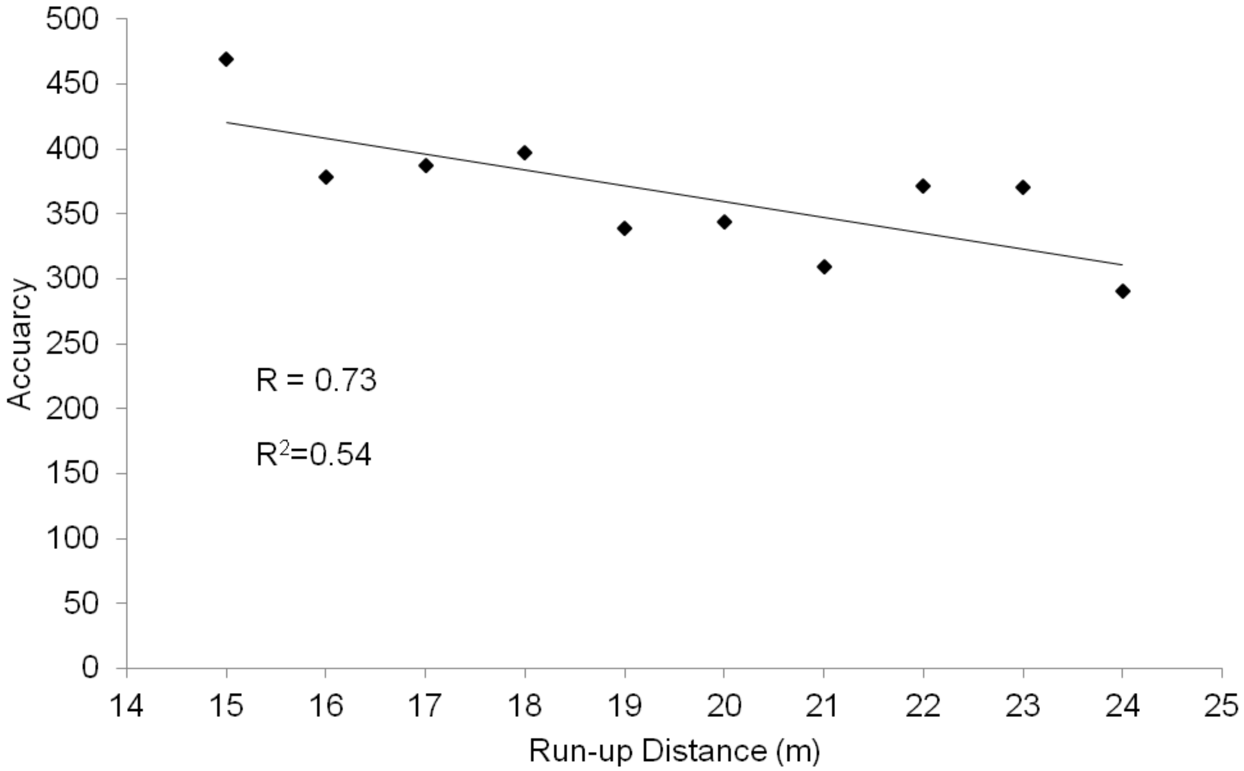


Figure 20: Players' run-up distances and the mean (±SD) accuracy achieved.

There was a fairly strong negative relationship (R = 0.73) between accuracy and run up distance (Figure 20). Players' mean run-up distance was 18.57 (± 2.4) m, and mean accuracy varied with players' different run-up distances (Figure 20). Accuracy decreases with longer run-ups; for example, accuracy ranged from 468.8 points at a run-up distance of 15m to 290.63 points at a run-up distance of 24m; a difference of 178.13 points. However, there was some variation in the data. Run-up distances of 22m and 23m showed slightly higher accuracy scores than those achieved at run-up distances of 19m-21m. The correlation (R = 0.73) between run-up distance and accuracy was statistically significant ($p<0.05$); this correlation does not necessarily mean causation; it simply shows that in this sample group, there was a trend for accuracy to decrease with an increase in run-up distance.

SUMMARY OF RESULTS

PARAMETER	SITE OF P<0.05	SIGNIFICANT DIFFERENCE (p<0.05)
Pre- versus post- protocol		
EMG	VM	No significant differences in RMS between normalisation and post- test measures at any speed
	VL	
	ST	
	BF	
Between speeds of protocol		
EMG	VM	There were significant differences for both pre- and post- measures between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h-1, 12km.h^{-1} - 21km.h^{-1} and 15km.h^{-1} - 21km.h^{-1}.
	VL	There were significant differences between speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h^{-1}, and 12km.h^{-1} - 21km.h^{-1} during the normalisation protocol, while the post- RMS increased significantly between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h-1, 12km.h^{-1} - 21km.h^{-1} and 15km.h^{-1} - 21km.h^{-1}.
	ST	There were significant differences between speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h-1, 12km.h^{-1} - 21km.h^{-1} and 15km.h^{-1} - 21km.h^{-1} during the normalisation protocol, while the post- RMS increased significantly between speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h-1, 12km.h^{-1} - 21km.h^{-1} and 12km.h^{-1} - 21km.h^{-1}.
	BF	There were significant differences for both pre- and post- measures between testing speeds 6km.h^{-1} - 12km.h^{-1}, 6km.h^{-1} - 15km.h^{-1}, 6km.h^{-1} - 21km.h^{-}1, 12km.h^{-1} - 21km.h^{-1} and 15km.h^{-1} - 21km.h^{-1}.
SJ	Lower limbs	Significant decrease in SJ pre- to post-protocol testing
ACCURACY	N/A	No significant changes

SPEED	**N/A**	Significant differences between overs one to four and over seven.
LOCAL RPE	**N/A**	Significant increase over time between all overs.
BODY DISCOMFORT	**Lower Back**	Significantly higher discomfort rating than the leading foot, leading calf, latissimus dorsi, leading knee, ankles, neck, and bowling-arm triceps.
	Bowling-arm shoulder	Significantly higher discomfort rating than the leading knee, ankles, neck, and bowling-arm triceps.
	Bowling-arm pectoral	Significantly higher discomfort rating than the leading foot, leading calf, latissimus dorsi, bowling-arm elbow, leading knee, ankles, neck, and bowling-arm triceps.
	Bowling-arm elbow	Significantly higher discomfort rating than the neck and bowling-arm triceps.
CORRELATIONS	**Run-up vs. speed**	There was a weak (R = 0.34) positive correlation between ball release speed and run-up distance
	Run-up vs. accuracy	There was a fairly strong negative relationship (R = 0.73) between accuracy and run-up distance

CONCLUSION

Despite players' perceiving the bowling spell as hard, experiencing more discomfort over time, and despite a significant decrement in SJ height over time, performance was not compromised in the 8-over fast bowling spell. This was except for ball release speed in the 7th over, which was significantly ($p<0.05$) slower than overs one to four. Further, muscle recruitment patterns remained unchanged during the bowling spell.

CHAPTER V

DISCUSSION

INTRODUCTION

This study aimed to investigate muscle activation patterns and musculoskeletal demands placed on university level fast bowlers, as well as perceptual stresses and performance during an eight over simulated bowling spell. Muscle activity and functional strength tests were performed prior to, and on completion of the work-bout. The work-bout used in this study was created to replicate an eight over bowling spell as accurately as possible. The accelerations and decelerations, specific to a fast bowling profile, were incorporated in the bowling spells. Fielding drills were also performed, to replicate the real match demands. It should also be noted that players included in this investigation performed at a university level, whereas the protocol informed by time motion analyses was on cricketers at an elite level.

BIOPHYSICAL MEASURES

Despite the fact that they were university level, the sample of 26 fast bowlers displayed similar age (Portus *et al.,* 2000), stature and mass (Noakes and Durandt, 2000; Taliep *et al.,* 2003) to previous studies (Table IV, pg 58). Players' mean body fat percentage was 14.05(±4.64) % with large variation between players. Similarly, a study performed on elite South African bowlers showed body fat percentages of just over 12% for bowlers (Noakes and Durandt, 2000). The results from the present study and previous literature are dissimilar to a study on the effects of fast bowling on performance in a study done in Cape Town, South Africa. This study showed body fat percentages in premier league players which were much higher (26.6%) and with less variation; standard deviation of 4.3% (Taliep *et al.,* 2003). Except for this latter study, the previous literature on elite and sub-elite fast bowlers shows a similar trend to the sample used into the present study. This may highlight the fact that fat percentages and slight differences in physical attributes are not the main determinant in the level players reach. Cricket generally and fast bowlers especially require high levels of skill, and cricketers today need to have quick reflexes and be able to maintain patience and concentration for long periods of time (Woolmer *et al.,* 2008).

LOWER LIMB MUSCULATURE

ELECTROMYOGRAPHY

Overall, the muscle activity patterns of both the quadriceps and hamstring musculature showed similar trends, all increasing as a function of speed. This was an expected result and it agreed with previous literature, which investigated muscle activity in relation to running velocity (Nilsson *et al*. 1985; Mizrahi *et al*., 1997 and Pincivero *et al*., 2000). The findings also showed similar muscle activation trends between speeds to other intermittent sport studies, namely cricket (Christie and Sheppard 2011), rugby (Christie and Cannon 2011) and also soccer (Rahhnama *et al*., 2006). The increase in muscle recruitment is suggested to be caused by the muscles having to be more active for a greater percentage of the gait cycle at these higher speeds (Nilsson *et al*., 1985). Therefore, as the speed of the protocol was increased, larger muscle recruitment was needed. Furthermore, muscles have been observed to be active earlier in the gait cycle at higher speeds (Nilsson *et al*., 1985).

Previous studies have shown a trend of increasing muscle activity as a result of exhaustive, repetitive exercise (Psek and Cafareli., 1993; Oberg, 1995; Kellis and Baltzopoulos,. 1999; Masuda *et al*., 1999; Yeung *et al*, 1999). These studies, however, were aimed at assessing different forms of muscle actions, as well as different intensities and durations. The recruitment of additional muscle fibres is known to compensate for the fatiguing active motor units which results in an increase in muscle activation (Gerdle *et al*., 2000). This adaptation would require alternative muscle groups or fibres to be activated so that the required workload is maintained. This allows the exercise to continue, as a constant work rate is maintained (Gerdle *et al.*, 2000). With conflicting evidence of muscle activation increasing and decreasing during intermittent sports (Yeung *et al.*, 1999), no certain conclusion can be drawn on the muscle activation patterns. For example, muscles may have fatigued, but to compensate for the fatigued muscle fibres, players may have recruited additional fibres. This would be represented as no change in results, much like this investigation. The previous studies highlight the differences that occur in muscle activation patterns between different muscle actions. It also indicates the differences in trends that eccentric activities have on the muscle activity, illustrating that eccentric actions which are very prevalant in fast bowling, are associated with larger amounts of fatigue. The theory that there may be a different type of fatigue that occurs with eccentric actions (Noakes and Durandt, 2000), is therefore very plausible.

Quadriceps Musculature

Increased muscle activation in the VM and VL was observed with increasing speeds during the EMG treadmill protocol, which is similar to the findings of previous soccer (Rahnama *et al.*, 2006), cricket (Christie and Sheppard, 2011), and rugby studies (Christie and Brown, 2009; Christie and Cannon, 2011).

In comparisons between pre- and post-protocol measures of the VM and VL muscle activation, no significant decreases were observed, however at the higher testing speeds, muscle activation did tend to decrease. Muscle activation dropped between 1.2 % and 11.4% in the quadriceps muscle group. The decreases in activation levels may be explained by the onset of muscle fatigue within the lower limbs (Billaut *et al.*, 2011). This can further be supported by the significant decrease in lower limb power output recorded. Previous studies also found decreases with regard to muscle activation patterns (Girard *et al.*, 2008; Girard *et al.*, 2009). For example, during tennis, quadriceps activation decreases (Girard *et al.*, 2008) and also during squash (Girard *et al.*, 2009), both of which are also highly intermittent sports. Muscular fatigue has been suggested to cause progressive decreases in muscle activity over time (Gonzalez-Alonso *et al.*, 2000; Mohr *et al.*, 2003; Rahnama *et al.*, 2003; Girard *et al.*, 2009). There are, however, contradicting studies, which have displayed increases in muscle activity with muscular fatigue (Christie and Brown, 2009). As SJ height decreased significantly over time, it is probable that the decrements in muscle activation, particularly of the hamstring musculature, were an indication of fatigue.

Hamstring Musculature

Larger muscle activity decreases were observed in the hamstring musculature. Within these decreases ST was shown to have greater decreases than the BF at higher speeds. The hamstring muscles are activated in the last third of the swing phase during terminal swing for sprinting (Schache *et al.,* 2010), and the hamstrings also eccentrically act to decelerate knee extension, in addition to opposing muscle activity of the quadriceps. During fast bowling the run-up requires acceleration and large amounts of hamstring activation. It is clear from the evidence, and involvement of the hamstring muscle group in sprinting and furthermore in deceleration, that fatigue and decreases in muscle activity in the hamstrings would be more prevalent than, for example, in the quadriceps. Following the delivery, players must come to a standstill in a very short space, requiring a quick deceleration. The large amounts of eccentric action in the hamstrings needed to decelerate players in such a short space may have resulted in functional force loss, or the decreases in muscle activity post-protocol at higher speeds. Although no significant decreases in muscle activation were observed in the hamstrings, a decreasing trend was evident. This is particularly apparent in the ST, which showed a 16.9% reduction in activation following the bowling spell. The ST experienced a larger decrease in muscle activation than the BF. This may have occurred as a direct result of the involvement of each muscle during fast bowling. This is purely speculative, as muscle activation was not recorded during a delivery, but before and after bowling spells. Although a lack of consistency between BF and ST muscle activation patterns has previously been documented (Pincivero *et al*., 2000), the present study identified a uniform trend – there have also been similar findings on batsmen within our laboratory (Christie and Sheppard, 2012).

The run-up is associated with large amounts of sprinting with bowlers covering 1.1 km at all-out sprinting intensities (Petersen *et al.,* 2010). Sprinting has therefore been identified as the main mechanism leading to fatigue, with the deceleration after sprinting placing a large eccentric load on the hamstring musculature. This elevates the fatigue experienced and increases the risk of injury (Greig *et al*., 2006). During sprinting, Pinniger *et al*. (2000) found that, as a result of fatigue, kinematics of movement and muscle activity had been altered. This causes a breakdown in the athlete's movement patterns (Bates *et al*., 1977) and increases the risk of injury (Greig *et al*., 2006). The trend of muscle activation decreasing at higher speeds may be caused by the re-allocation of muscular work due to the players' altered kinematics (Bates *et al*., 1977; Pinniger *et al*., 2000). Furthermore, altered kinematics is a major cause of hamstring injuries due to the dual innervations of the BF (Brooks *et al*., 2005). Because of poor co-ordination, the different muscles that make up the hamstrings activate independently at different times (Brooks *et al*., 2005). This can be seen in the present study, with the decreases in ST muscle activation being substantially higher than in the BF. It is clear that the stop-start nature, and continuous accelerating and decelerating, that is characteristic of intermittent sports, causes decreased strength of the hamstring muscle group in particular (Greig *et al*., 2006). The bowling technique or kinematics were however not closely monitored or measured. Thus no conclusion about the kinematics or alterations in bowling technique can be made and thus further studies should be performed to identify any such adaptations to players' bowling.

FUNCTIONAL STRENGTH

There was a significant ($p<0.05$) decrease in power output of players' lower limbs as a result of the bowling protocol. Decreased drop-jumps have been linked to decreases in muscle power (Horita *et al*, 1999). The intermittent pattern involved in fast bowling and the frequent stretch-shortening cycle movements somewhat explain these results. These changes may also be attributed to fatigue as there was a trend for muscle activation to decrease post-protocol, at higher running speeds. These reductions in activation levels may have been associated with a concomitant decrement in force production (Kellis and

Baltzopoulos, 1998), acting as a protective mechanism against injury. Houghton *et al.* (2012), investigating the physical strain placed on batsmen during a century batting simulation protocol, found a significant ($p<0.05$) decrement in maximal SJ height following the protocol, which was attributed to muscular fatigue (Houghton *et al.*, 2012). Although this was done in batsmen, the same has not been found for bowlers. For example, Duffield *et al*. (2008) measured vertical jump efforts before, during and directly after different bowling spells. There were two bowling spells consisting of six overs each; these were separated by 45 minutes of light activity. Duffield *et al*. (2008) showed no significant changes in vertical jump and power output. Furthermore, Taliep *et al.* (2003), using the drop jump as a measure of functional strength change, following a 12-over simulated bowling spell, found no significant differences in drop jump heights. Although Taliep *et al.* (2003) used a different method to assess lower body muscle power.

The reason for the significant drop in power in this study could be a combination of continuous eccentric muscle action causing functional consequences such as the reduced force production (Clarkson *et al.,* 1992; Enoka, 1996; Fridén and Lieber, 1992; Byrne *et al*., 2004), and the experience levels of the sample players. As these results were different from those previously found, the differences are more probably influenced by the different samples, or the experience and inherent strength differences of these samples. If players are at a university level, as opposed to players that are premier, semi-professional and professional level, they may be more susceptible to the eccentric muscle damage and fatigue. Nevertheless training programmes should be developed which include eccentric training movements to assist players in coping with these stresses, which are likely to occur during real match play, and perhaps reduce their risk of injury by delaying the onset of fatigue (Woolmer & Noakes, 2004).

PERCEPTUAL PARAMETERS

RATINGS OF PERCEIVED EXERTION

‘Local’

The players’ ‘local’ RPE was observed to progressively and significantly ($p< 0.05$) increase as a function of exercise duration. On completion of the first over, players rated ‘Local’ Ratings of Perceived Exertion as 7.4(±0.8), while at the end of the eighth over it was 15.04(±1.34). At the end of the bowling spell players therefore classified their perceived effort as ‘heavy’ in the workload category (Borg,1970). Despite players being instructed to maintain the same bowling intensity and effort and which was likely to have occured, perceived effort continued to increase as a function of time. The interesting aspect about these findings is that Borg’s (1970) RPE scale is commonly used as an indicator of exercise intensity and not exercise duration. However, recent research has supported this exercise duration effect (Noakes and Vlismas, 2011), and even in a cricketing context (Christie and Pote, 2011).

The probable reason for this increase could be related to musculoskeletal changes over time. So, while intensity of effort was probably unchanged, repetitive loading on the musculature was perceived by the players. This was demonstrated in the decrements in SJ post the bowling spell. It is highly plausible that the repeated eccentric actions involved in the run-up and delivery of the ball resulted in microscopic tears in the muscles ((Mann *et al.*, 1986; Devlin, 2000; Byrne *et al.*, 2004; Abbiss and Laursen., 2005) over time which the bowlers accurately perceived.

Body Discomfort

Perceived discomfort was observed to increase with each additional over within the protocol. This is seen by the increases in the total number of areas recorded and the severity of these areas (Table VII, pg 68). Expectedly, players indicated body discomfort most commonly in the lower back, while the front foot was also shown to cause discomfort, as in previous literature (Elliot *et al.,* 1992; Hardcastle *et al.,* 1992; Elliot *et al.,* 1993). Studies have shown that there is no single cause for the high incidence of lower back injuries. It is rather a combination of factors which may predispose fast bowlers to injuries (Elliot *et al.,* 1992). One of the major causes of lower back injuries is suggested to be overuse. With the game demands increasing, with additional forms of the game and increased matches being played, players are required to perform in more matches. Volume and intensity (Dennis *et al.,* 2005) as well as conditioning (Gregory *et al.,* 2002) play a vital role in injury incidence. Overuse injuries occur as a result of continuous microtrauma, where numerous forces contribute to produce a fatigue effect (Dennis *et al.,* 2005). The relationship between the delivery stride in particular, and bowlers experiencing large forces to the front foot (Elliot *et al.,* 1993), lower back injuries, and back pain (Elliot *et al.,* 1992; Hardcastle *et al.,* 1992) has been highlighted. The reasons for these and the other problem discomfort sites may be the unnatural nature of bowling, requiring players to stoop, twist and stretch forwards with each delivery. Further, large mechanical forces are placed on fast bowlers' lower limbs, back and upper body during ball delivery.

The increase in players' body discomfort, increased with a similar tendency to the 'local' RPE ratings, as a function of time. No lower limb discomfort in the quadriceps or hamstrings was found during the bowling spell. In relation to the muscle activity results, the body discomfort ratings are in agreement. However, in comparison to the SJ results, large decrements in power output and functional strength were observed. One would expect players to be aware of discomfort in the lower limbs. It is hypothesized that perhaps the lower limb discomfort recovered almost immediately after the delivery, and was not severe enough to persist. As the lower back and leading ankle became more fatigued, bowlers may have altered their action, resulting in altered muscle fibre recruitment in the lower limbs. The load may thus have been shared over greater fibres. Other studies have shown slightly altered bowling actions, a tendency of slightly altered bowling actions as a function of time have been shown during, a 12-over spell (Burnett *et al.*, 1995) and an eight-over spell (Portus *et al.,* 2000). Relationships between the biomechanical changes and performance therefore may exist, as well as increased stress on certain parts of the player's body. This may, for example, cause an increased 'local' RPE and body discomfort rating during the spell. Players may change bowling actions to reduce discomfort ratings, or sub-consciously alter bowling actions to avoid body discomfort as a whole. However, bowling action and technique was not measured during this investigation, but may be important in explaining body discomfort, fatigue and injury. Further investigations into the associations between muscle strength, muscle activity, and bowling technique should be done.

PERFORMANCE MEASURES

Accuracy was not compromised by the 8-over bowling spell, a finding similar to other studies that have investigated accuracy during six (Stretch and Lambert 1999; Duffield *et al*. 2008), eight (Portus *et al.,* 2000) and 12-over spells (Taliep *et al.,* 2003). Portus *et al.* (2000) observed a trend, although non-significant, with accuracy decreasing in the latter overs of the eight over spell. A large variation in bowling accuracy was evident in these findings, which have been observed previously in premier league (Taliep *et al.,* 2003), sub-elite and elite fast bowlers (Stretch and Lambert, 1999; Portus *et al.*, 2000; Duffield *et al*., 2008). The main studies that have previously measured players' accuracy over a bowling spell, have all used similar but slightly different techniques to measure accuracy, but with similar results (Portus *et al.*, 2000; Taliep *et al,.* 2003; Duffield *et al.*, 2008). Taliep *et al.* (2003) used a target area which was placed on the pitch by the players, while Duffield *et al*. (2008) used a grid-based target. Accuracy was measured in relation to how close each delivery came to the target area. This differed from Portus *et al.* (2000), who used both pitch-orientated target areas and a target suspended in front of the stumps. The results indicate that accuracy is not affected by the bowling spell, however it is highly variable (Portus *et al.*, 2000; Taliep *et al.,* 2003).

There was a significant ($p<0.05$), negative correlation ($R = 0.73$, $R^2 = 0.54$) between a player's run-up distance and accuracy; players having a longer run-up tend to bowl less accurately. Another reason for accuracy being significantly lower with the longer run-up may be associated with fatigue, as these players are covering more distance over time. This fatigue may occur in the upper body or the lower limb musculature, or a combination of both; as this was not measured, this is purely speculative but if this is the case, it may influence performance. There was no significant, positive ($R = 0.34$, $R^2 = 0.12$) correlation between players' run-up distance, and ball release speed. These correlations, however, may have been affected by the run-up distance being limited to a range of 15m – 25m. This may cause weakness, soreness and a decrease in force production by the damaged muscles. The altered kinematics seen during repeated sprinting efforts may result in the high variation in accuracy results. There was no correlation between players' perceived effort and accuracy. Players who felt the protocol was of 'heavy' stress did not bowl less accurately than the players who found the protocol relatively easier.

For comparative purposes, ball release speed has been converted to $m.s^{-1}$. In this study, mean ball release speed of players for the full bowling spell was 30.5 (±1.5) $m.s^{-1}$, which was similar, although slightly lower, than previous studies on fast bowlers. Other studies have found ball release speeds ranging from 31.3 (±1.5) $m.s^{-1}$ (Portus *et al.,* 2000, Taliep *et al.,* 2003) to 34.92 (±1.42) $m.s^{-1}$ (Duffield *et al.*, 2008). This may be attributed to the performance level and experience of the player samples. While other studies ranged from premier league to professional players, this study focused on university level players.

The explanation for why the 7th over was slower, and in contrast to all other previous studies, is difficult. This finding could be an anomaly with no plausible explanation. However, it may be a 'pacing effect' to conserve energy for the end spurt evident in the final over. This has been evidenced in many continuous exercise bouts (Foster *et al*., 1993; St Clair Gibson *et al.,* 2006; Mauger *et al.,* 2009) and more recently, in activities of an intermittent nature (Baron *et al.,* 2009; Billaut *et al*., 2011; De Koning *et al*., 2011). The drop in ball release speed in over seven could thus tentatively be attributed to an internal conscious or sub-conscious 'pacing' strategy (Billaut *et al*., 2011; De Koning *et al*., 2011).

However, without comparison trials, this is difficult to say particularly as this 'pacing' effect would be likely to occur earlier in the bowling spell and not in the penultimate over. The previous research on ball release speed further incline the belief that the results in the present study occurred because of other factors, or as an anomaly, and not as a direct result of 'pacing strategies'. Further, numerous studies show compelling arguments towards no change in ball release speed, over various length bowling spells (Burnett *et al.,* 1995; Portus *et al.,* 2000; Duffield *et al*., 2008), with no studies, to the author's knowledge, identifying any form of 'pacing strategy' in fast bowling spells.

For example, Portus *et al.* (2000) revealed no significant changes in mean ball speed during an eight over spell. This supports the findings of Duffield *et al*. (2008) who found no differences in ball release speed, over a repeated six over spell. Similarly, Burnett *et al*. (1995) reported that ball release speed remained constant throughout a 12-over bowling spell. In contrast, Taliep *et al.* (2003) observed a significant difference in the ball release speed during a 12 over simulated bowling spell. The ball release speed significantly decreased from the 6th over, with overs seven to 12 showing significantly slower ball release speeds than the first 6 overs. It is important to discover why such similar studies have produced conflicting results. Further research, into the differences in methodologies, revealed that some of the previous research did not incorporate all deliveries of these bowling spells. During an eight over spell, Portus *et al.* (2000) measured ball speed in overs two, five and eight only. Not included was over seven, which was where the significant decreases were identified, in this investigation. Randomly selected balls were also measured, which ensured bowlers maintained performance. Burnett *et al.* (1995) measured only the 5th and 6th deliveries of each over, and did not include accuracy data, which may have influenced bowler's ball release speed. As Taliep *et al.* (2003) suggests, an error in estimating the average ball speed could occur. Even a slight change in bowling speed during the unmeasured overs would therefore not reflect in the results. While Duffield *et al.* (2008) measured all deliveries, there was an original spell of six overs, which was separated by 45 minutes of light activity, before the repeated six over spell was performed. This means that the bowling spells may have been too short to display similar results as a continuous eight and 12 over bowling spell. In all the previous literature, although some conflicting results have been reported, there is no evidence of ‘pacing’ strategies.

There was no significant correlation between ball release speed and accuracy (P=0.33). With the significant decrease in ball release speed observed during over seven, players maintained accuracy. These may be related, as the bowler delivers a slower ball in order to maintain accuracy. This however fails to explain the increase in ball release speed and the absence of change in accuracy in corresponding overs.

Physiological tests in other studies on fast bowlers showed no changes to explain the decreases in ball release speed occurring in the latter overs of a bowler’s spell (Taliep *et al.,* 2003). It was theorized that lower back pain, and higher lower back injury incidence may be associated with these performance decrements (Taliep *et al.,* 2003). It is well documented that fast bowling is a common cause of lower back pain and many lower back injuries (Elliot *et al.,* 1992; Hardcastle *et al.,* 1992). In this investigation, lower back muscle activity and strength was not measured. However from body discomfort recordings there clearly is discomfort in this region, with 50% of players experiencing lower back discomfort during the eight over spell, which could explain the decrement in bowling speed. Furthermore, although not focused on in this investigation, previous literature has shown the tendency of players to alter their bowling actions during bowing spells (Burnett *et al.,* 1995; Portus *et al.,* 2000). The biomechanical, muscular strength and activation patterns of the lower back should be further investigated. This will help gain a better understanding of lower back fatigue and discomfort.

CONCLUSION

Muscle activity, although non-significant, showed a decreasing trend at higher testing speeds, and functional strength measures indicated that there were significant changes in lower limb muscle strength pre- versus post-protocol measures. Interestingly however, no player indicated the lower limb areas as uncomfortable. ‘Local” RPE values were shown to significantly increase over time, from over two until the end of the bowling spell. This was attached to a gradual increase in total body discomfort experienced by players over time. Although the protocol was repeated only once, performance responses were similar to those found in previous research. Players' accuracy was not shown to significantly decrease over the eight over bowling spells. Further, ball release speed was not negatively affected except for the reduction in ball release speed in the 7th over.

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CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

This study aimed to determine the musculoskeletal demands placed on specific lower limb musculature of fast bowlers, as well as the perceptual stresses and performance differences resulting from a simulated fast bowling spell. To the author's knowledge, no previous studies have assessed changes in surface muscle activity as a result of fast bowling. Research on fatigue and performance during a fast bowling spell, and cricket in general, has become more important, as the evolution of the sport has resulted in higher demands and stresses on the players. Stressors include alternative forms of the game and an increase in the number of matches required of players. Not only does this place increased stress on players, it also reduces the time they get to rest between games (Noakes and Durandt, 2000; Nunes and Coetzee, 2007). Fast bowlers experience stresses all over the body during each game, as recruitment of the limbs, trunk and shoulder occurs during each delivery. However it is very clear that the majority of injuries occur in the lower limbs, and fast bowlers experience the highest incidence of injury of all players. Therefore the main measures of interest were changes in lower limb functional muscle strength; performance measures; and the perceptions of effort during a bowling spell.

SUMMARY OF PROCEDURES

Little attention has been given to investigating muscle fatigue during cricket, specifically in fast bowlers. The main focus of this study relied on accurately replicating a bowling spell, while investigating its effects on the lower limb musculature and, specifically, changes in lower limb muscle strength and perceptions of effort and performance. A work-bout was developed based on time motion analyses of games.

Twenty six players from the Rhodes University squad and Rhodes University Internal league teams volunteered, and were selected to undergo testing. Players were required to bowl speeds of 100km.h^{-1} or higher, and meet a set of inclusion criteria. Players were required to attend two 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, and to fully explain all procedures to possible participants prior to testing. In addition, this first session allowed for habituation with the treadmill, the jump meter and all other equipment involved in experimentation.

The second testing session involved electrode attachment sites being identified on the player's dominant leg. The areas were then shaved, wiped with an alcohol swab and left to dry, to ensure good connectivity. EMG electrodes were then attached in the direction of the muscle fibres, positioned in such a way as to limit interference from surrounding muscles and ensure good connectivity to the muscles concerned. One neutral electrode was attached to the player's biceps, as this is an uninvolved muscle and eliminated electrical impedance.

Pre- and post- measures of muscle activity and functional strength of the lower limbs were recorded in the Department of Human Kinetics and Ergonomics. The protocol took place at the Kingswood High Performance Centre, which is near to the initial testing site. The protocol involved players bowling eight overs (48 balls). During the protocol, accuracy, ball release speed and perceptual measures were recorded at the end of each over. After the protocol, players were driven back to the Human Kinetics and Ergonomics Department where post-testing measures were completed.

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

Biophysical variables: Muscle activity and functional strength

Perceptual variables: 'Local' RPE and body discomfort

Performance variables: Accuracy and ball release speed

SUMMARY OF RESULTS

For all muscles it was shown that, as the speed increased, so did the muscle activity in players' lower limbs. This showed a direct relationship between speed and RMS of the relevant muscle. There were no significant changes in muscle activity pre- versus post-protocol. There was, however, a general trend of muscle activity showing a decrease at higher testing speeds. The highest percentage decrease occurred in the hamstring muscle group, specifically at the fastest running speeds. The highest percentage decreases in muscle activity, in the quadriceps muscle group, occurred at the slowest testing speed.

There were significant ($p<0.05$) decreases in vertical jump height and peak power of players following the simulated eight over bowling spell.

'Local' RPE displayed a significant ($p<0.05$) increase with each additional over. 'Local' RPE ratings were observed to reach the 'heavy' category, which clearly indicates the players perceiving the eight over spell as hard. The players' highest indicated discomfort area was in the lower back, with 13 players perceiving discomfort in this region following the eight over spell. The shoulder and chest were two other areas where players indicated discomfort, with eight players selecting the dominant shoulder. Seven players complained of discomfort in the dominant side pectoral muscle, leading foot and dominant latissimus dorsi muscle. Interestingly, the dominant pectoral showed the highest body discomfort ratings amongst players. The opening overs showed players experiencing discomfort in the elbow and dominant triceps area. This discomfort was seen to decrease over time with most of the players. In the latter three overs, players began to experience discomfort in the leading knee and leading ankle. The only muscular discomfort area for players in the lower limb region was the leading calf, with three players experiencing discomfort in their leading calves during the eight over spell.

There were no significant changes in accuracy between overs and there were large inter-individual differences in accuracy points of players. The ball release speed observed during over seven was shown to be significantly ($p<0.05$) lower than overs one to four. Mean ball release speed for the group as a whole ranged from 108.38km.h^{-1} (± 5.48) to 110.63km.h^{-1} (± 5.79). The significantly lower ball release speed observed during over seven may be a result of players' internal conscious/sub-conscious pacing mechanism, but this theory is not well understood and should therefore be further investigated.

STATISTICAL HYPOTHESES

MUSCULOSKELETAL HYPOTHESES

With respect to Hypothesis 1, regarding no difference between functional strength parameters, the null hypothesis can be rejected as significant ($p<0.05$) differences were found pre- versus post- protocol.

With respect to Hypothesis 2, which proposed no differences in muscle activity, the null hypothesis is accepted for all muscles (VM, VL, ST and BF) at all speeds (6,12,15,and 21km.h^{-1}). All muscles showed no significant differences in muscle activity post-protocol.

PERCEPTUAL HYPOTHESIS

With respect to Hypothesis 3, stating no differences in local ratings of perceived exertion (RPE) over time between conditions, the null hypothesis is to be rejected, as significant ($p<0.05$) increases were observed in 'local' ratings of perceived effort over time.

PERFORMANCE HYPOTHESIS

With respect to Hypothesis 4, the null hypothesis proposed no differences in accuracy over time. In this instance, the null hypothesis is tentatively retained as accuracy remained unchanged over time.

With respect to Hypothesis 4b, the null hypothesis proposed no differences in speed over time. The null hypothesis is thus tentatively retained in this case as there were no differences in ball release speed over time. This excludes the significant ($p>0.05$) decrease in over seven. For this over the null hypothesis is rejected.

CONCLUSION

It is clear that the protocol developed to accurately simulate a fast bowling spell significantly affects the perceptual responses over time. The intermittent movements required also had an effect on the musculoskeletal system, with the lower limb muscles showing significantly lower power output post-protocol. The players' ability to produce power suggests a possible increased risk of injury in the lower limb musculature over time. This can be attributed to the short intense braking that is required after each delivery, and the unique type of fatigue caused by eccentric actions on muscle. However, there were no differences in muscle activity although there was a non-significant trend for decrements in muscle activation at higher speeds. Although non-significant, the hamstring musculature in particular showed the largest decrements at higher speeds. The players' power output and perceived strain appears to indicate the presence of fatigue in players although this was not supported by muscle recruitment changes.

The players' perceived effort during the protocol significantly increased over time. The body discomfort readings corresponded to the 'local' RPE values: as the 'local' RPE increased, more areas of discomfort were shown by players. The area which displayed the most occurrences of discomfort was the lower back. Surprisingly, with the large decrements in muscle power of the lower limbs, no discomfort was indicated for the quadriceps or hamstring musculature.

Ball release speed was shown to be significantly lower in over seven than in overs one to four, following an increase in speed to over eight. This may be tentatively explained by the ‘pacing effect’. However, it is more likely that the results in the present study occurred because of other factors, or as an anomaly. Accuracy showed much variation between each over, but no significant differences were recorded over time. Although the protocol was repeated only once, performance responses were similar to previous research.

RECOMMENDATIONS

This investigation involved the testing of players’ dominant legs. Fast bowling requires different roles for the players’ dominant and non-dominant legs. The muscle activity changes may be different for these different roles. Further, muscle recruitment and muscle activity testing should allow testing of both limbs, so that comparisons can be made.

Isokinetic strength testing would add validity to this investigation. The squat jump test was used to measure the functional strength of players, however this is a field test, and it shows only the functional strength. Isokinetic testing would allow more accurate data for both eccentric and concentric strength changes. This allows for a more in-depth analysis of the mechanisms of fatigue for fast bowlers.

Power output was calculated using a prediction equation. This equation involved the use of players’ squat jump height and mass. As further investigations take place with fast bowlers, it would be beneficial to assess power output using a more direct measure - the use of a force plate to perform a vertical jump would achieve this.

Accuracy assessment improvements could be made. The line and length of each delivery is very important when assessing performance. With the accuracy methods used to assess performance in fast bowlers, limitations were highlighted. The length of ball is an important aspect to accuracy, therefore a method of analysing the length of each ball should be included, as well as inclusion for bowlers who may not be used to bowling directly for the stumps. To elaborate, many fast bowlers indicated that it was hard to change the way they bowled, and therefore constantly aimed at hitting the wickets. Bowlers were more accustomed to bowling down the offside - balls that may be recognized as a poor delivery with the accuracy methods used in the investigation were in actual fact recognized as a good delivery by players.

Training interventions should be included pre-season for fast bowlers, ensuring maximum eccentric training takes place. This should be followed by testing with the purpose of investigating the impact of the eccentric training. This will allow a greater knowledge of the mechanisms that may be involved in the players fatiguing, and training programmes that may limit fatigue and increase players' performance could then be developed.

As the players used in this investigation were from university and played cricket at a university level, the results gained are limited to university and cannot fully be applied to professional players. Further investigations should take place, to assess the muscle activity of semi-professional and professional fast bowlers.

There are different bowling techniques (front-on, side-on and mixed action) which can be adopted by bowlers. In future investigations, these should be recorded so that any variation as a result of different techniques can be avoided.

The EMG data were analysed using custom-written software to compute the root mean square (RMS) value. The way in which data is reduced and represented should be consistent among studies. This would allow for more comparisons to be made between studies. Sharing this information would also help improve research and understanding of muscle recruitment observed in cricket.

The kinematics of gait during the players’ run-up and delivery were not recorded in this study, and further investigations would be necessary to establish whether - and how - these compensations or changes were being made.

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APPENDIX A: GENERAL INFORMATION

ETHICAL APPROVAL

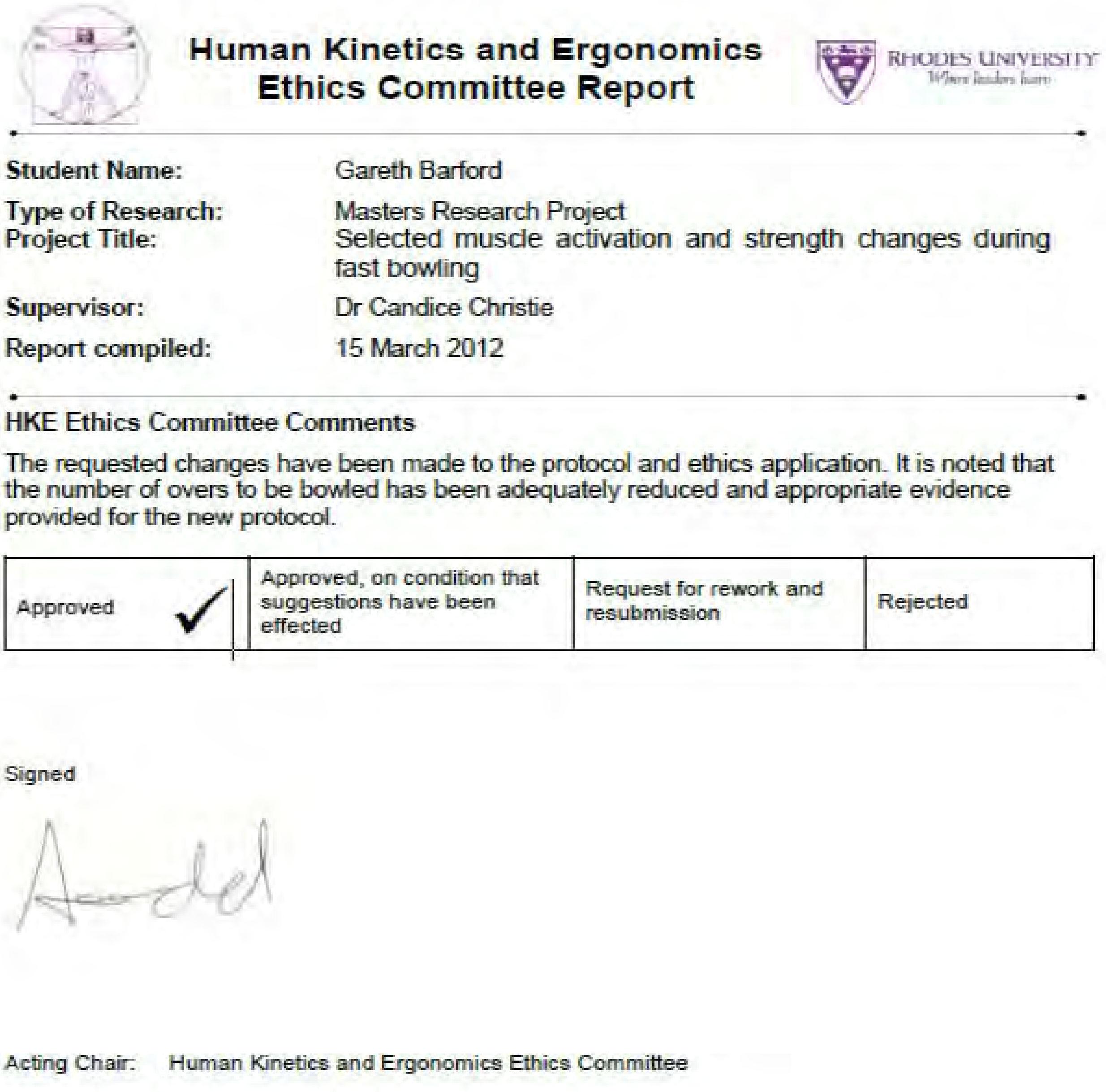
PLAYER CONSENT FORM

PHYSICAL ACTIVITY QUESTIONNAIRE

PRE TEST INSTRUCTIONS

EQUIPMENT CHECKLIST

ETHICAL APPROVAL



Human Kinetics and Ergonomics Ethics Committee Report

RHODES UNIVERSITY
Where leaders learn

Student Name: Gareth Barford

Type of Research: Masters Research Project

Project Title: Selected muscle activation and strength changes during fast bowling

Supervisor: Dr Candice Christie

Report compiled: 15 March 2012

HKE Ethics Committee Comments

The requested changes have been made to the protocol and ethics application. It is noted that the number of overs to be bowled has been adequately reduced and appropriate evidence provided for the new protocol.

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

Signed

Acting Chair: Human Kinetics and Ergonomics Ethics Committee

PLAYER CONSENT FORM

RHODES UNIVERSITY
Grahamstown • 6140 • South Africa

HUMAN KINETICS AND ERGONOMICS

Cell: 0845554527 E-mail: g07b0409@campus.ru.ac.za

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

CHANGES IN MUSCLE RECRUITMENT, FUNCTIONAL STRENGTH AND RATINGS OF PERCEIVED EFFORT DURING AN 8-OVER BOWLING SPELL: IMPACT ON PERFORMANCE

Do hereby give my consent to act as a subject in the above named research.

I am fully aware of the procedures involved as well as the potential risks and benefits attendant to my participation as explained to me verbally and in writing. In agreeing to participate in this research I waive any legal recourse against the researchers of Rhodes University, from any and all injuries sustained. This waiver shall be binding upon my heirs and personal representatives. I realize that it is necessary for me to promptly report to the researchers any signs or symptoms indicating any abnormality or distress. I am aware that I may withdraw my consent and may withdraw from participation in the research at any time. I am aware that my anonymity will be protected at all times and that all the information collected may be used and published for statistical or scientific purposes.

I have read the information sheet accompanying this form and understand it. Any questions that may have occurred to me have been answered to my satisfaction.

SUBJECT (OR LEGAL REPRESENTATIVE):

______________________	______________________	__________
(Print name)	(Signed)	(Date)

PERSON ADMINISTERING INFORMED CONSENT:

______________________	______________________	__________
(Print name)	(Signed)	(Date)

WITNESS:

______________________	______________________	__________
(Print name)	(Signed)	(Date)

PHYSICAL ACTIVITY SCREENING QUESTIONNAIRE

Name:__________________________

Code:__________________________

MEDICAL HISTORY

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

☐ Heart problems
☐ Peripheral vascular disorders
☐ High/low blood pressure
☐ Epilepsy
☐ Anaemia
☐ Asthma
☐ Emphysema
☐ Migraine
☐ Eye problems
☐ Hypoglycaemia
☐ Diabetes
☐ Hyperthyroidism
☐ Other (specify):____

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

____
____
____

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

____
____
____

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

____
____
____

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

____
____
____

OTHER HABITS

Please tick appropriate box:

Do you smoke?

YES	NO

If Yes, how many cigarettes per day:_______

EXERCISE HISTORY

Do you exercise regularly?

YES	NO

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

1	2	3	4	5	6	7	0

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

YES	NO

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

- ☐ Jogging_____
- ☐ Hockey_____

☐ Rowing_____
☐ Swimming_____
☐ Tennis_____
☐ Rugby_____
☐ Cricket_____
☐ Soccer_____
☐ Squash_____
☐ Other_____

PRE-TEST INSTRUCTIONS

On arrival at the department, please inform the researcher or research assistants, if there are any factors known to you that may influence the results, for example, if you have flu, or are 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. Datalogger
2. Electronic Toledo Scale (Model 8141)
3. Harpenden Stadiometer
4. Electrodes
5. Adhesive double-sided tape
6. Razor
7. Harpenden Skinfold Calipers
8. Alcohol Swobs
9. Fiximol Adhesive
10. Quinton 611 incremental Treadmill
11. Data Sheets (Questionnaire and Consent Forms)
12. RPE Scales
13. Radar Gun
14. Radar Gun Tripod
15. Accuracy Board
16. Jump Meter
17. 4 Piece Cricket-ball

APPENDIX B: DATA COLLECTION

ORDER OF PROCEDURES

RPE SCALE

BODY DISCOMFORT SCALE

TIME SHEET

DATA COLLECTION SHEET

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, age)
6. Explain performance measures
7. Explain the data sheets for perceptual parameters
8. Select dates for experimental sessions

Session II: Testing

1. Welcome player
2. Recap Protocol and ask if player has any illness or injuries since last meeting
3. Prepare dominant limb for electrode attachment
4. Attach electrodes with additional taping, attach cables to data logger and check
5. everything is working
6. Perform warm-up and stretches
7. Perform the pre-protocol EMG protocol
8. Perform squat jump
9. Drive to Kingswood HPC
10. Recap data sheets and performance scoring zones

11. Cricket specific warm-up
12. Perform protocol
13. Return to department
14. Perform post testing
15. Thank player for taking part
16. Give player R30 Steers voucher, funded by the NRF

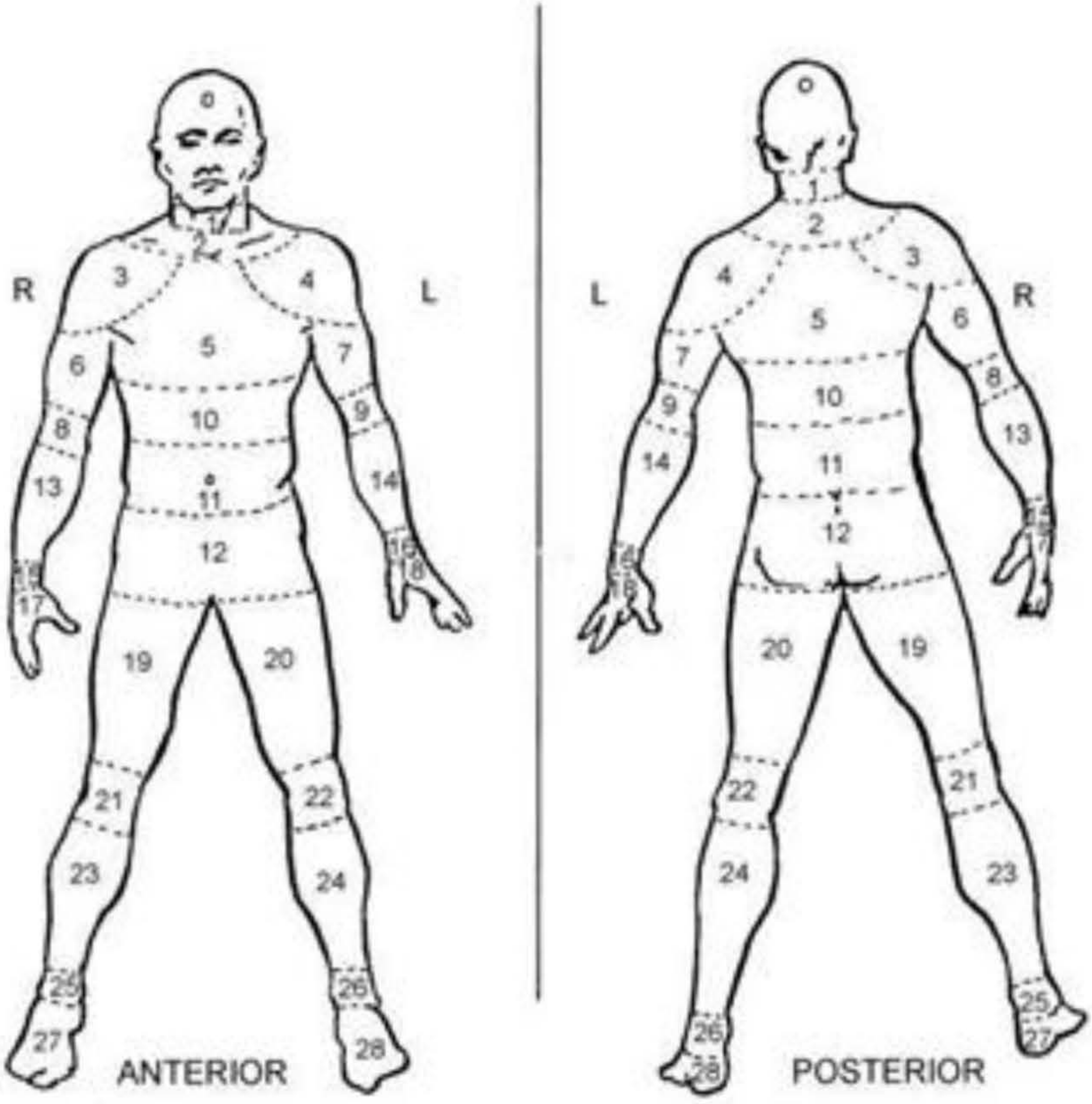
THE BORG (RPE) SCALE

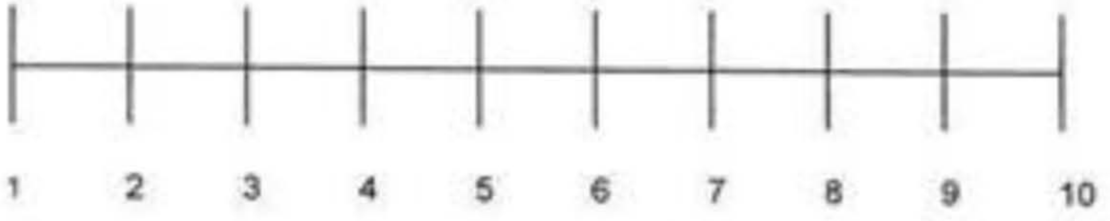
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (Heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

EXPLANATION TO PLAYERS

During the eight over bowling spell, you will be asked to estimate how hard you feel you are working. The value that you give should represent how hard you perceive your muscles in the lower limbs to be working. A rating of six corresponds to your feelings of exertion while standing quietly, whereas a rating of 20 corresponds to maximal exertion.

THE BODY DISCOMFORT SCALE





EXPLANATION TO THE PLAYERS

At the end of each over once you have estimated your ‘local’ RPE, you will be asked to rate your perception of body discomfort during the over just completed. Please try determine the exact location of discomfort or pain experienced at that point in time, For example; if discomfort is in one side only, this should be stated. The map provided will allow you to point to the region and select an intensity between one and ten, one corresponding to ‘very comfortable’, while ten corresponds to ‘extreme discomfort’.

TIME SHEET

Steps	Time (min:s)	During (min:s)
Delivery 1	00:00	0.39
Delivery 2	00:39	0.39
Delivery 3	01:17	0.39
Delivery 4	01:59	0.39
Delivery 5	02:34	0.39
Delivery 6	03:13	0.39
Change-over	03:54	01:20
Fielding Drills	05:14	03:13
Change-over	09:08	01:20
Start Next Over	10:28	End
Bowling Total		03:54
Rest Total		02:40
Fielding Drills		03:54

EXPLANATION TO THE PLAYERS

A delivery will be performed every 39 seconds. You will be informed five seconds before each delivery. At the end of each over there is a one minute 20 second break. ‘Local’ RPE and body discomfort will be performed during this time.

DATA SHEETS

	Accuracy						Body Discomfort
	Ball 1	Ball 2	Ball 3	Ball 4	Ball 5	Ball 6	
Over 1							
Over 2							
Over 3							
Over 4							
Over 5							
Over 6							
Over 7							
Over 8							

	Speed (km/hr)						Local RPE
	Ball 1	Ball 2	Ball 3	Ball 4	Ball 5	Ball 6	
Over 1							
Over 2							
Over 3							
Over 4							
Over 5							
Over 6							
Over 7							
Over 8							

Squat Jump		
	Pre	Post
1		
2		
3		

APPENDIX C: SUMMARY REPORTS

STATISTICAL ANALYSES

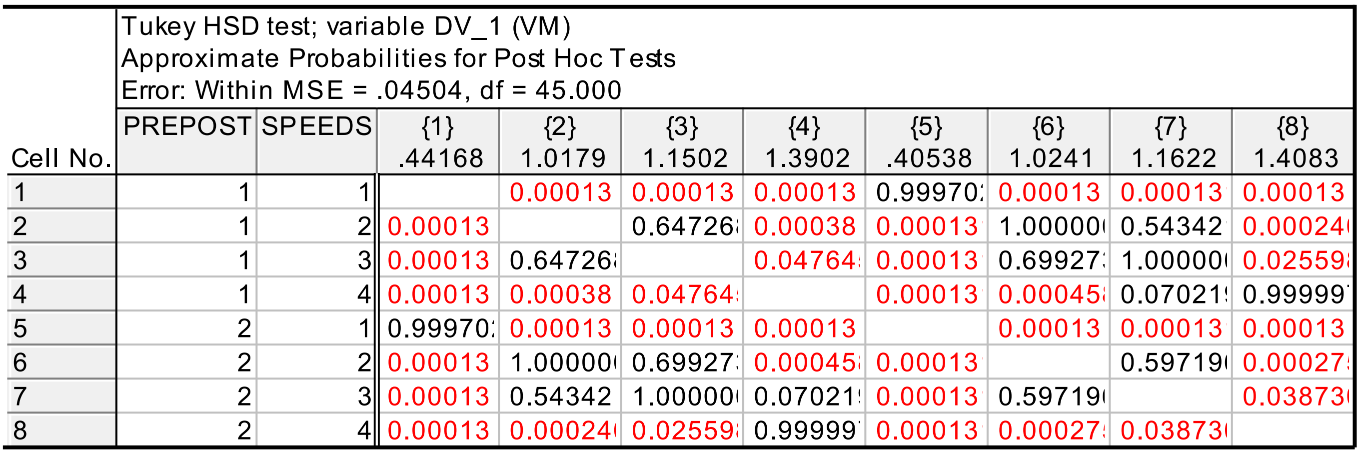
BIOPHYSICAL RESPONSES

PERCEPTUAL RESPONSES

PERFORMANCE RESPONSES

BIOPHYSICAL RESPONSES

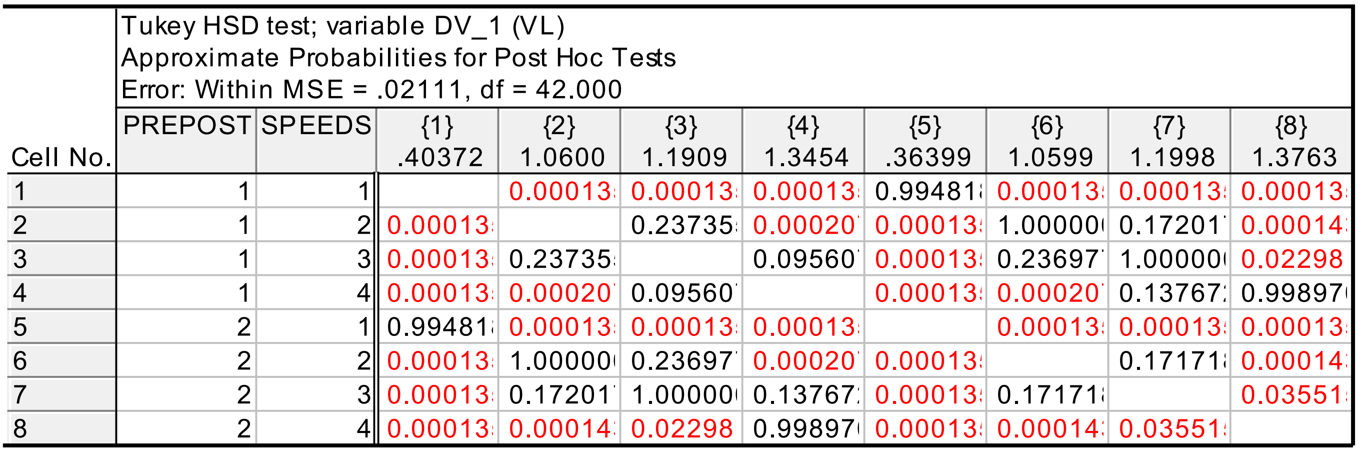
General Linear models (GLM) on the vastus medialis with changes in speed



Tukey HSD test; variable DV_1 (VM)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .04504, df = 45.000

Cell No.	PREPOST	SPEEDS	{1} .44168	{2} 1.0179	{3} 1.1502	{4} 1.3902	{5} .40538	{6} 1.0241	{7} 1.1622	{8} 1.4083
1	1	1		0.00013	0.00013	0.00013	0.99970	0.00013	0.00013	0.00013
2	1	2	0.00013		0.64726	0.00038	0.00013	1.00000	0.54342	0.00024
3	1	3	0.00013	0.64726		0.04764	0.00013	0.69927	1.00000	0.02559
4	1	4	0.00013	0.00038	0.04764		0.00013	0.00045	0.07021	0.99999
5	2	1	0.99970	0.00013	0.00013	0.00013		0.00013	0.00013	0.00013
6	2	2	0.00013	1.00000	0.69927	0.00045	0.00013		0.59719	0.00027
7	2	3	0.00013	0.54342	1.00000	0.07021	0.00013	0.59719		0.03873
8	2	4	0.00013	0.00024	0.02559	0.99999	0.00013	0.00027	0.03873	

GLM on the vastus lateralis with changes in speed



Tukey HSD test; variable DV_1 (VL)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .02111, df = 42.000

Cell No.	PREPOST	SPEEDS	{1} .40372	{2} 1.0600	{3} 1.1909	{4} 1.3454	{5} .36399	{6} 1.0599	{7} 1.1998	{8} 1.3763
1	1	1		0.00013	0.00013	0.00013	0.99481	0.00013	0.00013	0.00013
2	1	2	0.00013		0.23735	0.00020	0.00013	1.00000	0.17201	0.00014
3	1	3	0.00013	0.23735		0.09560	0.00013	0.23697	1.00000	0.02298
4	1	4	0.00013	0.00020	0.09560		0.00013	0.00020	0.13767	0.99897
5	2	1	0.99481	0.00013	0.00013	0.00013		0.00013	0.00013	0.00013
6	2	2	0.00013	1.00000	0.23697	0.00020	0.00013		0.17171	0.00014
7	2	3	0.00013	0.17201	1.00000	0.13767	0.00013	0.17171		0.03551
8	2	4	0.00013	0.00014	0.02298	0.99897	0.00013	0.00014	0.03551	

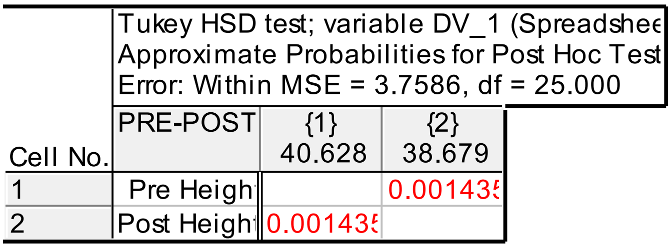
GLM on the semitendinosus with changes in speed

	Tukey HSD test; variable DV_1 (VM) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .04199, df = 39.000									
Cell No.	PREPOST	SPEEDS	{1} .42621	{2} .97687	{3} 1.1644	{4} 1.4325	{5} .47002	{6} 1.0142	{7} 1.1980	{8} 1.3178
1	1	1		0.00012	0.00012	0.00012	0.99913	0.00012	0.00012	0.00012
2	1	2	0.00012		0.25987	0.00014	0.00013	0.99970	0.11081	0.00199
3	1	3	0.00012	0.25987		0.02620	0.00012	0.53374	0.99985	0.50765
4	1	4	0.00012	0.00014	0.02620		0.00012	0.00021	0.07523	0.81268
5	2	1	0.99913	0.00013	0.00012	0.00012		0.00012	0.00012	0.00012
6	2	2	0.00012	0.99970	0.53374	0.00021	0.00012		0.28311	0.00769
7	2	3	0.00012	0.11081	0.99985	0.07523	0.00012	0.28311		0.77739
8	2	4	0.00012	0.00199	0.50765	0.81268	0.00012	0.00769	0.77739	

GLM on the biceps femoris with changes in speed

	Tukey HSD test; variable DV_1 (VM) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .03290, df = 48.000									
Cell No.	PREPOST	SPEEDS	{1} .43465	{2} .97005	{3} 1.1280	{4} 1.4673	{5} .42533	{6} .95134	{7} 1.1480	{8} 1.4754
1	1	1		0.00013	0.00013	0.00013	1.00000	0.00013	0.00013	0.00013
2	1	2	0.00013		0.20421	0.00013	0.00013	0.99998	0.10436	0.00013
3	1	3	0.00013	0.20421		0.00016	0.00013	0.10901	0.99998	0.00015
4	1	4	0.00013	0.00013	0.00016		0.00013	0.00013	0.00025	1.00000
5	2	1	1.00000	0.00013	0.00013	0.00013		0.00013	0.00013	0.00013
6	2	2	0.00013	0.99998	0.10901	0.00013	0.00013		0.05108	0.00013
7	2	3	0.00013	0.10436	0.99998	0.00025	0.00013	0.05108		0.00020
8	2	4	0.00013	0.00013	0.00015	1.00000	0.00013	0.00013	0.00020	

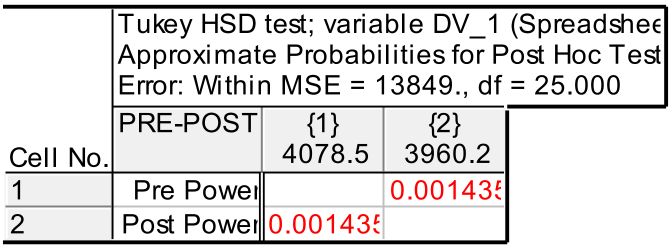
GLM of Squat Jump (SJ) height pre- and post-protocol



Tukey HSD test; variable DV_1 (Spreadshee
Approximate Probabilities for Post Hoc Test
Error: Within MSE = 3.7586, df = 25.000

Cell No.	PRE-POST	{1} 40.628	{2} 38.679
1	Pre Heigh		0.00143
2	Post Heigh	0.00143	

GLM of Peak Power (Watts) pre- and post-protocol

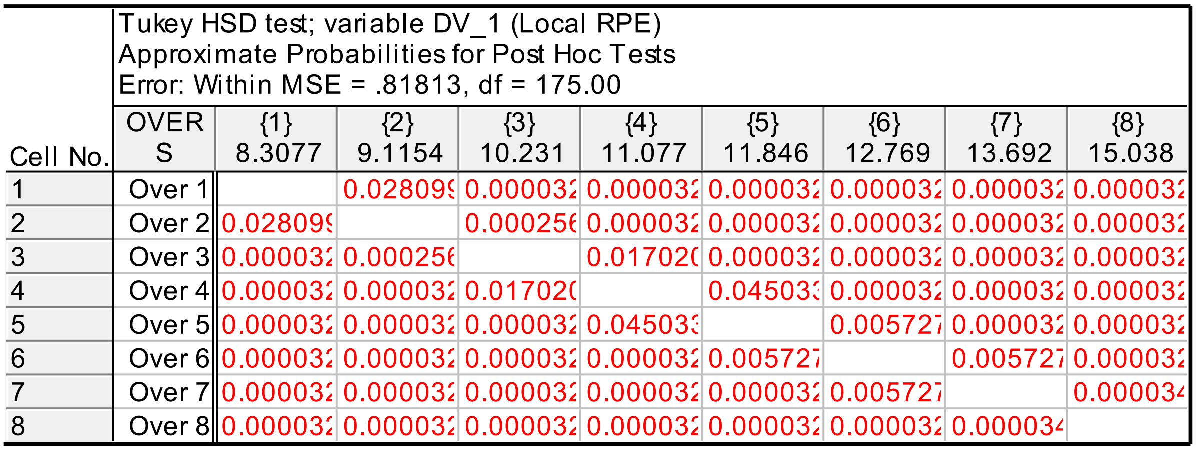


Tukey HSD test; variable DV_1 (Spreadshee
Approximate Probabilities for Post Hoc Test
Error: Within MSE = 13849., df = 25.000

Cell No.	PRE-POST	{1} 4078.5	{2} 3960.2
1	Pre Powe		0.00143
2	Post Powe	0.00143	

PERCEPTUAL RESPONSES

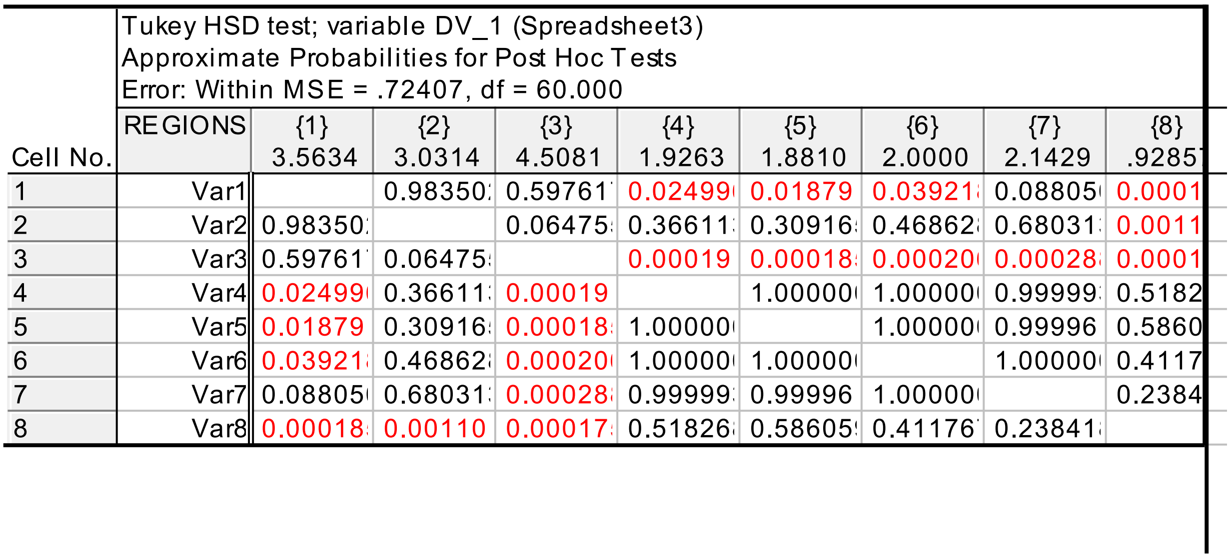
ANOVA of the ‘local’ RPE responses of the players over time



Tukey HSD test; variable DV_1 (Local RPE)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .81813, df = 175.00

Cell No.	OVERS	{1} 8.3077	{2} 9.1154	{3} 10.231	{4} 11.077	{5} 11.846	{6} 12.769	{7} 13.692	{8} 15.038
1	Over 1		0.02809	0.000032	0.000032	0.000032	0.000032	0.000032	0.000032
2	Over 2	0.02809		0.00025	0.000032	0.000032	0.000032	0.000032	0.000032
3	Over 3	0.000032	0.00025		0.01702	0.000032	0.000032	0.000032	0.000032
4	Over 4	0.000032	0.000032	0.01702		0.04503	0.000032	0.000032	0.000032
5	Over 5	0.000032	0.000032	0.000032	0.04503		0.005727	0.000032	0.000032
6	Over 6	0.000032	0.000032	0.000032	0.000032	0.005727		0.005727	0.000032
7	Over 7	0.000032	0.000032	0.000032	0.000032	0.000032	0.005727		0.000034
8	Over 8	0.000032	0.000032	0.000032	0.000032	0.000032	0.000032	0.000034	

ANOVA of players body discomfort areas, and the scores of these areas.



Tukey HSD test; variable DV_1 (Spreadsheet3)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = .72407, df = 60.000

Cell No.	REGIONS	{1} 3.5634	{2} 3.0314	{3} 4.5081	{4} 1.9263	{5} 1.8810	{6} 2.0000	{7} 2.1429	{8} .9285
1	Var1		0.98350	0.59761	0.02499	0.01879	0.03921	0.08805	0.0001
2	Var2	0.98350		0.06475	0.36611	0.30916	0.46862	0.68031	0.0011
3	Var3	0.59761	0.06475		0.00019	0.00018	0.00020	0.00028	0.0001
4	Var4	0.02499	0.36611	0.00019		1.00000	1.00000	0.99999	0.5182
5	Var5	0.01879	0.30916	0.00018	1.00000		1.00000	0.99996	0.5860
6	Var6	0.03921	0.46862	0.00020	1.00000	1.00000		1.00000	0.4117
7	Var7	0.08805	0.68031	0.00028	0.99999	0.99996	1.00000		0.2384
8	Var8	0.00018	0.00110	0.00017	0.51826	0.58605	0.41176	0.23841	

PERFORMANCE RESPONSES

Repeated measures ANOVA of the ball release speed of the players over time

	Tukey HSD test; variable DV_1 (Spreadsheet2 in Speed) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 3.7722, df = 175.00								
Cell No.	OVERS	{1} 110.39	{2} 110.63	{3} 110.62	{4} 110.15	{5} 109.75	{6} 109.33	{7} 108.38	{8} 109.23
1	Over 1		0.999872	0.999906	0.999815	0.935503	0.496861	0.004768	0.374931
2	Over 2	0.999872		1.000000	0.987014	0.737673	0.235911	0.000844	0.157581
3	Over 3	0.999906	1.000000		0.988576	0.749320	0.245249	0.000914	0.164670
4	Over 4	0.999815	0.987014	0.988576		0.996090	0.796619	0.023843	0.684248
5	Over 5	0.935503	0.737673	0.749320	0.996090		0.993689	0.178676	0.978123
6	Over 6	0.496861	0.235911	0.245249	0.796619	0.993689		0.653891	1.000000
7	Over 7	0.004768	0.000844	0.000914	0.023843	0.178676	0.653891		0.770708
8	Over 8	0.374931	0.157581	0.164670	0.684248	0.978123	1.000000	0.770708	

Repeated measures ANOVA of the accuracy of the players over time

	Tukey HSD test; variable DV_1 (Spreadsheet2 in Accuracy) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 7917.4, df = 175.00								
Cell No.	OVERS	{1} 343.27	{2} 351.92	{3} 369.23	{4} 376.92	{5} 387.50	{6} 389.42	{7} 386.54	{8} 390.38
1	Over 1		0.999969	0.966285	0.873731	0.625393	0.571575	0.651879	0.544496
2	Over 2	0.999969		0.996982	0.972661	0.837883	0.797165	0.856439	0.775132
3	Over 3	0.966285	0.996982		0.999986	0.995765	0.992162	0.996982	0.989627
4	Over 4	0.873731	0.972661	0.999986		0.999880	0.999634	0.999937	0.999404
5	Over 5	0.625393	0.837883	0.995765	0.999880		1.000000	1.000000	1.000000
6	Over 6	0.571575	0.797165	0.992162	0.999634	1.000000		1.000000	1.000000
7	Over 7	0.651879	0.856439	0.996982	0.999937	1.000000	1.000000		1.000000
8	Over 8	0.544496	0.775132	0.989627	0.999404	1.000000	1.000000	1.000000	