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Intrinsic factors in pace bowlers: the predisposition to injury and the relationship with performance

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Intrinsic Factors in Pace Bowlers: The Predisposition to Injury and the Relationship with Performance

Benita Olivier

Supervised by Prof AV Stewart and Dr W McKinon

A thesis submitted to the Faculty of Health Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree Doctor of Philosophy.

Johannesburg, 2013

Declaration

I, Benita Olivier, declare that the work contained in this thesis is my own work, except to the extent indicated in the acknowledgements section.

This thesis is being submitted for the degree of Doctor of Philosophy, at the University of the Witwatersrand, Johannesburg, South Africa.

This work has not been submitted for any other degree or examination in this or any other university.



Signature of Candidate

23 October 2013

Abstract

The significance of this research lies in the fact that it makes a meaningful contribution to the development of comprehensive injury prevention programmes. The studies included in this thesis investigate technique-related intrinsic factors where injury is prevented at the expense of performance as well as intrinsic factors where there is potential for both injury prevention and performance to be simultaneously optimised. The cricket pace bowler is prone to injury due to the high load nature of the pace bowling action involving a complex sequence of forceful actions, consisting of practiced, particular movements. Various injury prevention programmes incorporating extrinsic factors have been studied and implemented previously, however the intrinsic factors associated with both injury and performance in pace bowlers have not yet been investigated sufficiently. In this thesis an overview of the literature includes the review of injuries sustained by pace bowlers, factors associated with injury and performance, and the kinematics of the pace bowling action. Premier league (amateur) cricket pace bowlers were recruited for this study. All pace bowlers were injury free at the start of the season. Details around past injuries as well as incidence of injuries were recorded throughout an eight month cricket season. Performance measures, namely ball release speed and accuracy, were measured during execution of the pace bowling action.

Included in this thesis are six original papers. The first five papers investigated the association between intrinsic factors, injury and performance, while the sixth paper described abdominal muscle adaptations in the pace bowler. The first paper (Chapter 2) investigated bowlers' ability to perform lumbo-pelvic movement control, static and dynamic balance tests at the start and at the end of a cricket season. Lumbo-pelvic movement control tests could not

discriminate between bowlers who sustained an injury during the cricket season and bowlers who did not. However, performance in the single leg balance test (SLBT) ($p=0.03$) and the star excursion balance test (SEBT) ($p=0.02$) as measured at the start of the season, was better in bowlers who did not sustain an injury during the season.

Paper 2 (Chapter 3) investigated lumbar proprioception (as measured by joint position sense) in the neutral lumbar spine position; as well as lumbar positions corresponding to those at front foot placement and ball release of the cricket pace bowling action in relation to previous injury and injury sustained during the cricket season under review. Lumbar reposition error in the sagittal plane (flexion-extension) was between 1.48˚ and 1.82˚ and in the frontal plane (left-right lateral flexion) it was between 0.81˚ and 0.88˚. Lumbar reposition error, as measured in two planes and in three different positions, was associated with self-reported general injuries, injuries sustained during the bowling action and especially, low back injury sustained in the past ($p<0.05$). From findings indicated in Papers 1, 2 and 3 (Chapters 2, 3 and 4) it can be postulated that if static balance, dynamic balance and lumbar proprioception can be improved in pace bowlers, their risk of lumbar injury may be reduced.

Paper 3 and 4 (Chapter 4 and 5) investigated the relationship between kinematic angles as measured in the power phase of the pace bowling action and injury, as well as performance, respectively. In Paper 3 (Chapter 4) a difference was found between lumbar spine lateral flexion positioning ($p=0.02$) at the start compared to at the end of the season in injured pace bowlers. The range of flexion between front foot placement and ball release at L1 is much greater in the non-injured group than in the injured group as measured at the end of the season ($p=0.03$). Bowlers who did not sustain an injury during the season displayed a larger

degree of absolute flexion at the start of the season than those who sustained an injury ($p=0.02$). Findings from Paper 4 (Chapter 5) are that the following absolute angles were positively correlated with higher ball release speeds at the start of the season: a more extended knee angle ($p=0.037$), a larger arm to thorax angle ($p<0.0001$), larger L1 ($p=0.01$), T10 ($p<0.0001$) and T7 ($p<0.0001$) segmental spinal lateral flexion and more global trunk left rotation ($p=0.02$). Paper 3 and 4 (Chapter 4 and 5) thus show that low back flexion and lateral flexion, and front knee kinematics, as found in the power phase of the pace bowling action, are associated with and may predict lower quarter injuries and performance outcomes in cricket pace bowlers.

The fifth paper (Chapter 6) hypothesised that correlations between front knee angle, knee reposition error, as a measure of proprioception, and ball release speed should be present, however no such correlation could be established. The correlations between joint reposition error in 140˚ of knee extension ($r=0.06$), 160˚ of knee extension ($r=0.30$), front foot placement ($r=0.22$) and ball release ($r=0.23$) positions were not statistically significant ($p>0.05$). Furthermore, correlations between knee position error and reproduced knee angles were also not statistically significant ($r=-0.35$ to $r=0.09$; $p>0.05$). It was concluded that static knee joint position sense is not associated with dynamic knee angle during the bowling action, or with ball release speed and that dynamic mechanisms may contribute to knee angles and bowling speeds.

The sixth study (Chapter 7) investigated and highlighted the possible muscle adaptations in absolute muscle thickness and activity as a consequence of the asymmetrical bowling action. The absolute thickness of the non-dominant obliquus abdominis internus (OI) was higher

than that of the dominant OI at the start ($p<0.0001$) as well as at the end of the cricket season ($p<0.0001$). At the start of the season the percentage change during the abdominal drawing in manoeuvre, thus a measure of muscle activity, was higher for the non-dominant OI than for the dominant OI ($p=0.02$). Absolute thickness of the dominant obliquus abdominis externus (OE) at rest was significantly higher at the end of the season compared with at the start of the season ($p<0.0001$). During right side active straight leg raise, the activity of the left transversus abdominis (TA) was significantly higher than that of the right TA during left side active straight leg raise ($p=0.03$) when measured at the end of the season. These asymmetries in abdominal muscle thickness and activity may contribute to the predisposition to low back injury in cricket pace bowlers or may occur in an attempt to protect the pace bowler against injury.

In conclusion, the high load nature of the pace bowling action allows for high ball release speeds to be attained but at the same time renders the pace bowler vulnerable to injury. Intrinsic factors found to be associated with both lower quarter injury and performance should be appropriately incorporated into injury prevention programmes in order to prevent the occurrence of injuries in the presence of the high load nature of the pace bowling action. Further research needs to be conducted on the effectiveness of these injury prevention programmes to prevent injury amongst pace bowlers.

Acknowledgments

Dr Warrick McKinon, thank you for always availing space in your diary for my project, thank you for your calm nature and for your amazing ability to solve any problem. Prof Aimee Stewart, thank you for your phenomenal research expertise and most of all for your wisdom from day one. Also, thank you for believing in this project and for providing financial support to develop Wits Physiotherapy's first mobile movement laboratory.

The pace bowlers who participated in this study, I appreciate your time and effort, and I enjoyed your enthusiasm for the game of cricket. To the research assistants who lifted the load during the data collection phase, you decreased my cortisol levels immensely.

I would like to express my sincere gratitude to the National Research Foundation, the Carnegie Foundation of New York and the South African Society of Physiotherapy – without financial support this project would not have been possible.

Dr Hellen Myezwa, our HOD, and all my colleagues in the Department of Physiotherapy for the inspiration given to me in different forms throughout my study period.

My family – my mother, for always showing interest in my well-being and "survival"; to my father, for teaching me to forget about the past, to live for the future and to keep the peace; to my three brothers and sisters in law, for all the happy conversations, braais, holidays and everything else that was needed for a balanced life.

Evah, for all the long hours of support to the Olivier household. Then, to my husband, Hansie…. thank you for the numerous “clinical reasoning sessions” around the pace bowling technique and how the biomechanics of it as perceived by coaches and players. Thank you for trying to convince me that I’m the best researcher, lecturer, physiotherapist, writer, reader, cook, mother, wife, golfer (non-inclusive list) out there ☺. Thank you for all your love and support. And to my two precious baby boys who each had their turn to accompany me “in situ” on my endeavours to complete this thesis.

To the Almighty… thank you Lord.

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List of Abbreviations

ASIS – anterior superior iliac spine

BKFO L – bent knee fall out (left)

BKFO R – bent knee fall out (right)

BR – ball release

DTP – dorsal tilt of the pelvis

EC – eyes closed

EO – eyes open

FFP – front foot placement

Flex – flexion

KLAT L – knee lift abdominal test (left)

KLAT R – knee lift abdominal test (right)

L – left

LM – Lumbar Multifidi muscle

LF – lateral flexion

OE – Oblique Abdominis Externus muscle

OI – Obliquus Abdominis Internus muscle

OLS L – one leg standing (on left)

OLS R – one leg standing (on right)

PLAKF L – prone lying active knee flexion left

PLAKF R – prone lying active knee flexion right

R – right

RB – rocking backwards

RE – reposition error

RF – rocking forwards

Rot – rotation

SEBT – star excursion balance test

SKE – sitting knee extension

SLBT – single leg balance test

TA – Transverses Abdominus muscle

WB – waiter's bow

Operational Definitions

Amateur pace bowler: A pace bowler who's main source of income is not as a result of playing cricket (King et al 2010).

Back foot placement phase: A phase in the pace bowling action defined from back foot contact to front foot contact, which is also called the delivery stride phase (Ranson et al 2008; Ferdinands et al 2009).

Biomechanics: The study of mechanical laws and their application to living organisms, especially the human body and its movement (Richards 2008).

Extrinsic factor: An extrinsic factor is a factor that is attributable to the environment around an athlete such as time of game, player position or exercise load (Meeuwisse 1994).

Fast bowler: Fast bowlers are bowlers who bowl at a speed of 140km/h or faster (Frost and Chalmers 2012).

Front foot placement phase: A phase in the pace bowling action defined from front foot contact to ball release, which also called the power phase (Ranson et al 2008; Ferdinands et al 2009).

Injury: For the purposes of this study an injury is defined as "a musculoskeletal condition that resulted in loss of at least one day of sporting activity or that occurred during a sporting

activity that required medical attention and which forced the bowler to quit the activity" (Dvorak and Junge 2000; Orchard et al 2005; Roussel et al 2009; Cross et al 2013).

Intrinsic factor: An intrinsic factor is a factor that is attributable to athlete him/herself (person-related), such as flexibility and strength (Meeuwisse 1994; Dvorak and Junge 2000; Orchard et al 2001; Orchard 2001; Cross et al 2013).

Kinematics: The study of the motion of the body without regard to the force acting to produce the motion (Richards 2008).

Kinetics: The study of the forces that produce, stop or modify motions of the body (Richards 2008).

Medium pace bowler: Medium pace bowlers are bowlers who bowl at a speed of 120–130 km/h (Frost and Chalmers 2012).

Pace bowler: Pace bowlers are bowlers who bowl at a speed of 120km/hr or faster (Frost and Chalmers 2012).

Reference list

References for the above operational definitions are included in the reference list in Chapter 1 (Literature Review).

Preface and Description of Thesis Sections

The inherent nature of the pace bowling action predisposes cricket pace bowlers to injury. Despite attempts to prevent injury in pace bowlers, a high incidence of injury amongst pace bowlers is still common. An investigation of intrinsic factors associated not only with injury, but also with performance could facilitate improvements to the current injury prevention methods. The work described in the chapters in this thesis aimed to investigate intrinsic factors, injury and performance in pace bowlers.

The literature relevant to this thesis is reviewed in Chapter 1 where after the relationship between intrinsic factors and injury is shown in studies described in Chapters 2, 3 and 4. Chapters 5 and 6 describe the relationship between intrinsic factors and performance measures. An intrinsic factor that adapts to the demands of the pace bowling action, namely abdominal muscle thickness and activity, is described in Chapter 7. Chapter 8 provides an overall discussion followed by a conclusion to the thesis in Chapter 9.

An overview of each chapter contained in this thesis will follow here:

Chapter 1 reviews the literature related to injury in pace bowlers, including the prevalence and type of injuries commonly sustained by pace bowlers. An examination of performance measures of ball release speed and bowling accuracy follow. Intrinsic and extrinsic factors commonly associated with injury and current injury prevention measures are also reviewed. The literature surrounding the specific intrinsic factors investigated in this study follows, including static and dynamic lower limb balance, lumbo-pelvic movement control and lumbar and knee proprioception. The definition, method of testing as well as association with injury

and performance are reviewed for each intrinsic factor. The kinematics and kinetics of the pace bowling action are then discussed and include information on the classification of the pace bowling action and its association with injury and performance.

Chapters 2 and 3 consist of two papers investigating the association between injury and intrinsic factors, including static and dynamic lower limb balance, lumbo-pelvic movement control and lumbar proprioception in the pace bowler. Chapter 2 compares the status of intrinsic factors as assessed at the start of a cricket season to the status at the end of the season in pace bowlers who did and those who did not sustain an injury during the season. In Chapter 3, injury variables include previous injury, injury sustained during the cricket season under review, specific low back injury as well as injury sustained during the bowling action are discussed. The paper in Chapter 2 has been accepted for publication in the *Journal of Science and Medicine in Sport*, and the paper in Chapter 3 has been accepted for publication in *The Spine Journal*.

Chapter 4 contains a paper submitted to the *Journal of Science and Medicine in Sport*. This chapter investigates the spinal and knee kinematics present in the bowling action and their association with lower quarter (low back and lower limb) injury. Spinal and knee kinematics, as measured at the start and again at the end of a cricket season are compared in injured and non-injured bowlers.

The relationship between performance measures and kinematic variables is investigated in **Chapter 5**. Correlations of ball release speed against various kinematic variables including front knee, arm to thorax and spinal angles, as well as ball release height as found at the start and at the end of a cricket season are explored. Knee angle classification and bowling

accuracy are briefly explored. This paper was submitted to the *Journal of Science and Medicine in Sport.*

Chapter 6 investigates an intrinsic factor, namely knee joint position sense, and its relationship with front knee angle and ball release speed. Joint reposition error was measured in two arbitrary positions (140˚ and 160˚ knee extension), as well as in two sport specific, functional positions namely each bowler's exact angles as measured at front foot placement and ball release. This paper has been accepted for publication by the journal *Gazzetta Medica Italiana*.

The side to side asymmetries in absolute muscle thickness and activity of the lateral abdominal wall in cricket pace bowlers are described in **Chapter 7**. Possible reasons for, as well as consequences of, side to side asymmetry in abdominal muscle thickness and activity are discussed in this chapter. The paper contained in Chapter 7 has been published by the *South African Journal of Sports Medicine*.

In **Chapter 8** the implications and significance of Chapters 2-7 in the light of the literature (Chapter 1) are discussed. More detailed and focussed discussion sections can be found in the discussion section of each respective paper. In Chapter 8 the nature of the pace bowling action, injury, performance, intrinsic factors, physical adaptations as a result of the pace bowling action, the relevance of assessment in functional sport-specific positions, assessment at both the start and the end of a cricket season as well as the use of user-friendly physical tests are discussed.

Chapter 9 concludes all the experimental results discussed in the previous chapters. It furthermore describes the significance, strengths and limitations of the thesis. Future research and clinical recommendations are also conferred. Note that references are listed at the end of each chapter and as a result an all-inclusive reference list was not included.

Appendices including sections that were removed from Chapter 4 due a limited word count, questionnaires, the information sheet, the informed consent form, the ethical clearance certificate as well as a table showing the status of the papers under review can be found in **Chapter 10**.

Journal Submissions Emanating from the Work Presented in this Thesis

Olivier B, Stewart AV, Olorunju SAS and McKinon W (2013) Static and Dynamic Balance Ability, Lumbo-Pelvic Movement Control and Injury Incidence in Cricket Pace Bowlers, *Journal of Science and Medicine in Sport* (in press)

Olivier B, Stewart AV and McKinon W (2013) Injury and Lumbar Reposition Sense in Cricket Pace Bowlers in Neutral and Pace Bowling Specific Body Positions, *The Spine Journal* (in press)

Olivier B, Stewart AV, Green AC and McKinon W (submitted 2013) Spinal and Knee Kinematics in Low Back and Lower Limb Injury in Cricket Pace Bowlers, *Journal of Science and Medicine in Sport* (under review)

Olivier B, Stewart AV, Green AC and McKinon W (submitted in 2013) Cricket Pace Bowling: A Longitudinal Study of Spinal and Knee Kinematics, Ball Release Speed and Bowling Accuracy, *Journal of Science and Medicine in Sport* (under review)

Olivier B, Stewart AV, Green AC and McKinon W (2013) Knee Joint Position Sense does not Correlate with Front Knee Angles or Ball Release Speed in Cricket Pace Bowlers, *Gazzetta Medica Italiana* (in press)

Olivier B, Stewart AV and McKinon W (2013) **S**ide to Side Asymmetry in Absolute and Relative Muscle Thickness of the Lateral Abdominal Wall in Cricket Pace Bowlers, *South African Journal of Sports Medicine,* 25(3):81-86

Conference Presentations Emanating from the Work Presented in this Thesis

Previous Conference Presentations

South African Society of Physiotherapy Congress – Bloemfontein, Free State

Date: 23 March 2012

Title: Movement Control and Balance Ability in Cricket Pace Bowlers

Type: Oral platform presentation

Presented by: Benita Olivier

Authors: Benita Olivier, Aimee Stewart, Steve Olorunju, Warrick McKinon

8th Annual International Conference on Kinesiology and Exercise – Athens, Greece

Date: 26 June 2012

Title: The Influence of Injuries Sustained prior to and during a Cricket Season on Lumbo-pelvic Movement Control, Static and Dynamic Balance Ability in Cricket Pace Bowlers

Type: Oral platform presentation

Presented by: Benita Olivier

Authors: Benita Olivier, Aimee Stewart, Steve Olorunju, Warrick McKinon

South African Society of Physiotherapy Sport Symposium – Johannesburg, Gauteng

Date: 3 November 2012

Title: Side to Side Asymmetry in Muscle Thickness of the Lateral Abdominal Wall in Cricket Pace Bowlers

Type: Oral platform presentation

Presented by: Benita Olivier

Authors: Benita Olivier, Aimee Stewart, Warrick McKinon

5th Cross Faculty Graduate Symposium – Johannesburg, Gauteng

Date: 1-2 August 2013

Title: Knee Joint Position Sense is not associated with Front Knee Angles or Ball Release Speed in Cricket Pace Bowlers

Type: Poster presentation (accepted)

To be presented by: Benita Olivier

Authors: Benita Olivier, Aimee Stewart, Andrew Green, Warrick McKinon

19th Congress of the European Society of Biomechanics – Patras, Greece

Date: 25-28 August 2013

Title: Spinal and Knee Kinematics Predict Lower Back and Lower Limb Injury in Cricket Pace Bowlers

Type: Oral platform presentation (accepted)

To be presented by: Benita Olivier

Authors: Benita Olivier, Aimee Stewart, Andrew Green, Warrick McKinon

Future Conference Presentations

The following abstract have been accepted for presentation to a conference that will take place in the near future:

15th Biennial Congress of the South African Sports Medicine Association – Port Edward, KwaZulu Natal (invited speaker)

Date: 24-27 October 2013

Title: Injury and Lumbar Reposition Sense in Cricket Pace Bowlers in Neutral and Pace Bowling Specific Body Positions

Type: Oral platform presentation

To be presented by: Benita Olivier

Authors: Benita Olivier, Aimee Stewart, Warrick McKinon

Contributions of Authors to the Project

As part of the declaration of this thesis, I acknowledge contributions by various individuals to this work as detailed below:

The experimental design, data collection and analysis for all work were devised by myself[a] in conjunction with my supervisors, Dr Warrick McKinon[b] and Prof Aimee Stewart.[a]

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Steve Olorunju[c] assisted with statistical analysis of the manuscript entitled: "Static and Dynamic Balance Ability, Lumbo-Pelvic Movement Control and Injury Incidence in Cricket Pace Bowlers" as more complex statistical procedures were applied. Statistical analysis of all other manuscripts was performed in conjunction with Warrick McKinon[b] and Aimee Stewart.[a] Advice was sought from statisticians based in the Faculty of Health Sciences

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CHAPTER 1 – Literature Review

1. Introduction to the Literature Review

The game of cricket is generally considered to be a sport of low injury risk (Orchard et al 2002) compared with other sports (Seward et al 1993). However, of all the various roles of the cricket player, the pace bowler has the highest risk of injury (Orchard et al 2002; Orchard et al 2006; Mansingh et al 2006; Stretch et al 2009; Stretch and Raffan 2011; Frost and Chalmers 2012). The pace bowler strives towards the adoption of a bowling technique with a relatively low injury risk that will at the same time allow for a fast and accurate delivery to the opposing batsman. Lower quarter injuries, namely lower back and lower limb injuries, are the type of injury most prevalent in the pace bowler (Orchard et al 2002; Orchard et al 2006; Mansingh et al 2006; Stretch et al 2009; Stretch and Raffan 2011; Frost and Chalmers 2012). The high prevalence of injury amongst pace bowlers exposes a great need for research of factors associated with injury and injury prevention.

The ultimate goal of studies investigating the link between both intrinsic (attributable to athlete him/herself) and extrinsic risk factors (attributable to the environment around an athlete), and injury, is to contribute to the development of injury prevention programmes. Injury prevention in turn has been a focus of research in its own right. Donnely et al (2012), Finch (2006) as well as Van Mechelen's (1992) recommends injury prevention research to be approached systematically by:

1. Identifying the incidence of common and serious injuries
2. Identifying risk factors (both intrinsic and extrinsic) for the most common and serious injuries
3. Implementation of preventative programmes based on modification of reversible risk factors
4. Monitoring success of intervention with on-going surveillance

This thesis focuses on the identification of intrinsic risk factors associated with injury, with an added component where the association of some intrinsic risk factors with performance are also studied.

Both extrinsic and intrinsic factors work in combination to predispose the bowler to injury. Extrinsic, or environment-related factors, include bowling workload, player position and time of play. Extrinsic factors are known to make the bowler more susceptible to injury, especially in the presence of intrinsic factors. Intrinsic, or person-related factors, have previously included muscle strength, flexibility, balance and biomechanics (Meeuwisse 1994; Orchard et al 2001; Orchard 2001; McBain et al 2012a; Cross et al 2013). This literature review aims to focus on the intrinsic factors that have already been studied, as well as candidate intrinsic factors that have not yet been related to injury in pace bowlers specifically. Various intrinsic factors that have been investigated in the current thesis include; static and dynamic lower limb balance, lumbo-pelvic movement control, lumbar spine and knee proprioception, and abdominal muscle architecture. Studies that have investigated intrinsic factors related to the kinematics of the pace bowling action will also be reviewed.

Although injury prevention is cardinal to the pace bowler and optimal performance depends on being injury free, the nature of the game of cricket is such that the pace bowler, like fielders, batsmen and wicket keepers, has to perform to contribute to the overall performance of the team. The strong pressure on the pace bowler to perform should be regarded in the light of the simultaneous strong need to remain injury free. The pace bowler utilises intrinsic factors to attain a high bowling speed, some of which may predispose the bowler to injury and some may be protective (Portus et al 2004; Loram et al 2005; Wormgoor et al 2010;

Crewe et al 2013b). In order to explore such factors in the light of both injury prevention and performance, this chapter will include a review of the literature on performance and some of the intrinsic factors that play a role in performance.

2. Injuries in Pace Bowlers

In this section, definitions of injury used in different studies are compared and contrasted, where after the literature on the prevalence of injuries in pace bowlers is reviewed. The focus is then refined to specifically trunk, lumbar and lower limb injury, before traumatic and non-traumatic injury, and intrinsic and extrinsic factors, are reviewed.

2.1 Definition of Injury

In the surveillance of injury, different definitions have been used. A consensus statement was developed with the aim to promote the use of consistent international injury definitions in cricket injury surveillance and in that way enable the comparison of injury statistics across countries (Orchard et al 2005b). This statement defined an injury as "any injury or other medical condition that either (a) prevents a player from being fully available for selection for a major match or (b) during a major match, causes a player to be unable to bat, bowl, or keep wicket when required by either the rules or the team's captain" (Orchard et al 2005b).

The above definition however only contains detail on the inability to participate in matches (Orchard et al 2005b). The following definition includes the participation in games as well as in practice. In the National Collegiate Athletic Association Injury Surveillance System "injury was reported if it occurred during an activity in an organized intercollegiate practice

or game that resulted in the inability to participate for at least 1 day beyond the day of injury" (Cross et al 2013).

Orchard et al (2005b) suggest that a broader definition that incorporates training and match participation can be used should the aim be to survey injuries more extensively: "'any medical condition that presents to medical staff, which affects a player's ability to perform during a match or training'' (Orchard et al 2005b). Although by using this definition, results cannot be compared between different studies (King et al 2010), a greater number of injuries can be captured for the purposes of a specific single study which may allow for a more sensitive analysis of injury.

In another study seeking to identify injury amongst soccer players, an injury was defined as "any physical complaint sustained by a player that made him seek medical assistance and that resulted from a soccer match or soccer training, forcing him to miss or being unable to take full part in future soccer training or match play (''time-loss'' injury)" (Engebretsen et al 2010). This is a detailed definition which also includes the inability to participate in both match and training situations, but like the definition in the consensus paper (Orchard et al 2005b), it includes all physical complaints and is not limited to musculoskeletal conditions only.

"Any musculoskeletal condition requiring time away from dancing" was the definition that was used in a study investigating injuries amongst dancers (Roussel et al 2009). In this definition it is specified that only musculoskeletal conditions should be reported (Roussel et al 2009). Such an approach allows for the exclusion of other medical illnesses that may have resulted in time away from participating in the sport. Although the National Collegiate

Athletic Association Injury Surveillance System definition also excluded the reporting of a variety of medical illnesses by using the word “injury” it is believed that by using the words “musculoskeletal condition” not only injury but also pain will be reported.

For purposes of the studies described in this thesis, a definition of injury needs to be wide enough to capture all significant injuries but at the same time exclude other medical illnesses was needed. Therefore, based on the definitions described above, the following definition was developed: “a musculoskeletal condition that resulted in loss of at least one day of sporting activity or that occurred during a sporting activity that required medical attention and which forced the bowler to quit the activity”.

“Not participating in a sporting activity” or “time loss injuries”, however depends on the number of games and training sessions taking place and the “requirement of medical attention” depends on the availability and access to medical services (Dvorak and Junge 2000). Although this definition is, thus still open to subjective interpretation, it is believed that amongst a homogenous group of players from the same country playing at the same level, these two factors are very similar for all participants.

2.2 Prevalence of Injuries in Pace Bowlers

The high prevalence and incidence of injury in cricket pace bowlers has been a concern in published research since as early as 1965 (Pye 1965). Successful on-going surveillance of injury depends largely on consensus in terms of injury definitions. The consensus statement paper attempts to create consistent injury definitions (Orchard et al 2005b). Injury surveillance in cricket has been conducted according to the injury surveillance consensus

paper (Orchard et al 2005b) in South Africa (Stretch et al 2009; Stretch and Raffan 2011), Australia (Orchard et al 2006), West Indies (Mansingh et al 2006) and New Zealand (Frost and Chalmers 2012).

Table 1 shows the incidence and prevalence of injuries amongst cricketers, namely batsmen, pace bowlers, spin bowlers and wicket keepers as they have been documented by studies investigating injury incidence.

Table 1. Injury incidence and prevalence rates amongst cricket players in different countries

Country	**Incidence (injuries/10 000hrs)***	**Prevalence (%)****
South Africa (Stretch and Raffan 2011) – international cricket players	90.00	3.80
South Africa (Stretch et al 2009) – provincial cricket players	30.00	8.00
Australia (Orchard et al 2006) – elite cricket players	32.30	8.23
West Indies (Mansingh et al 2006) – international and domestic cricket players	44.65	9.70
New Zealand (Frost and Chalmers 2012) – elite cricket players	51.60	10.20

*Number of injuries occurring during the cricket season expressed as the number of injuries per 10 000hours of exposure to play (Orchard et al 2005a)
**The average percentage of players who are not available for selection for a match (Orchard et al 2005a)

Compared to the incidence and prevalence of injuries sustained by cricketers in general, the occurrence of injuries sustained by pace bowlers is far higher. The injury prevalence amongst Australian pace bowlers was 14.37%, while the prevalence for batsmen was 4.32%, for spin bowlers 3.7% and for wicket keepers 2.0% (Orchard et al 2006). Similar injury rates were

found amongst New Zealand cricketers where a prevalence rate of 18.7%, 5.4%, 5.5% and 3.8% were found for pace bowlers, batsmen, spin bowlers and wicket keepers, respectively (Frost and Chalmers 2012). In both studies, bowling was also the most common activity in which injuries occurred when compared to batting, fielding and wicket keeping (Orchard et al 2006; Frost and Chalmers 2012). It is also clear that pace bowling accounted for more than three times the number of injuries compared to spin bowling. Except for the two studies mentioned above, prevalence rates specific to pace bowlers were not reported in any of the other studies listed in Table 1.

Amongst South African international cricketers, of all injuries occurring over two seasons (2004-2006), bowling accounted for the highest percentage of injury (27%) sustained when compared with batting (23%), fielding (24%), fitness training (3%) and other/illnesses (24%) (Stretch and Raffan 2011). The authors did not state how many of the 36 cricketers were pace bowlers and they also did not specify how many injuries were sustained due to pace bowling and how many due to spin bowling. Not only in international but also in South African provincial cricketers bowling was the cause of the highest percentage (29%) of all injuries sustained, compared with batting 19%, fielding 27%, fitness 3% and other medical illnesses 22% of injuries (Stretch et al 2009). In the West Indies, bowling also accounted for most of the injuries amongst cricketers (Mansingh et al 2006).

Comparison of injury rates with other sports is difficult as the same definition of *prevalence* of or *incidence* of injury is not always used. In general, cricket is considered a safe sport when compared with other sports. The overall injury prevalence in cricket is 8% (Orchard et al 2002), while it is 15% in Australian football, 16% in first grade rugby league and 13% in state rugby union (Seward et al 1993). The injury prevalence rates in these "more dangerous"

sports compare well with the injury prevalence rates reported in pace bowlers (Orchard et al 2006; Frost and Chalmers 2012). Furthermore, it is interesting to consider that Australian football, rugby league and rugby union are regarded as contact sports, while pace bowling is not (McBain et al 2012a), but still has the same high prevalence of injury. It gives a clue as to the importance of injury prevention in pace bowling.

Injury incidence levels in baseball are at 36.1 injuries per 10 000 hours of athlete exposure (Posner et al 2011). This is in line with the injury incidence rates of cricketers in general, as shown in Table 1. Pitchers experienced a 34% higher incidence of injury when compared to fielders (Posner et al 2011). Injury incidence rates specific to pace bowlers are not available and thus cannot be compared with injury incidence rates in pitchers. It is however clear that pitchers also suffer more injuries than fielders. The same phenomenon exists in cricket where pace bowlers suffer more injuries than batsmen and wicket keepers (Orchard et al 2006; Stretch and Raffan 2011; Frost and Chalmers 2012).

Literature on the most common body areas injured by the pace bowler, namely the trunk, low back and lower limb will be reviewed further in the subsequent section.

2.3 Trunk, Lumbar and Lower Limb Injuries

Trunk, lumbar and lower limb injuries are the most common types of injuries in pace bowlers. Injuries specifically sustained by bowlers or those related to the bowling action were reported amongst West Indies and Australian bowlers (Orchard et al 2002; Mansingh et al 2006).

West Indies pace bowlers sustained 21 injuries over the surveillance period of seven months. Of the 21 injuries, eight injuries, thus 38 %, were lumbar spine injuries, while 20% were lower limb injuries, 14% were abdominal injuries and 24% upper limb, and 4% were due to other causes like illness (Mansingh et al 2006). Within the above mentioned figures it is not stated which injuries were sustained during any of the other roles (batting, wicket keeping or fielding) in cricket. However, injuries sustained during bowling were analysed in the same study. These figures include spin bowlers although the spin bowlers only sustained two injuries during the surveillance period. It is interesting to note that all injuries sustained during bowling were to the trunk, low back and lower limbs, where 57% were lumbar injuries, 14% were trunk injuries and 29% were lower limb injuries (Mansingh et al 2006). From these statistics the assumption can be made that bowlers are at higher risk of trunk, lumbar and lower limb injury directly due to performance of the bowling action which is an integral part of their role in the cricket team.

Australian first class pace bowlers missed 21% of playing time due to lumbar spine injuries, 49% due to lower limb injuries and 12% due to trunk injuries (abdominal and rib injuries), 15% due to upper limb, head and neck injuries, and 3% due to other medical illnesses (Orchard et al 2002). In the same study, 58% of injuries that occurred during bowling were lower limb injuries, 11% were lumbar injuries, 23% were trunk injuries, 9% were upper limb injuries and 2% were due to other medical illnesses (Orchard et al 2002).

A similar injury incidence pattern was reported by Stretch and Venter (2005) who monitored the injuries of 11 provincial teams, namely 783 cricketers, over six cricket seasons. Of the bowling injuries sustained during their study (Stretch and Venter 2005), 55% were lower

limb injuries, 33% were back and trunk injuries and 12% were upper limb, head, neck and face injuries.

From the above studies it is clear that injuries sustained by pace bowlers or during the bowling action account mostly for trunk, lumbar and lower limb injuries. For this reason, more information on why trunk, lumbar and lower limb injuries are so common amongst pace bowlers will follow.

Compared to other sports, different patterns in the distribution of injuries according to body area are noted and different theories are relevant in each case. Amongst football players the majority of injuries were to the lower extremities (Dvorak and Junge 2000). The majority of injuries in football are contact, traumatic injuries. However this is not the case in pace bowling as the biomechanical factors inherent to the "high load" bowling action is likely to predispose a bowler to injury (Foster et al 1989; Portus et al 2004; Ferdinands et al 2009; Stuelcken et al 2010). Pitchers in both baseball and soft ball, suffer mainly from upper limb injuries, while cricket pace bowlers suffer mainly from lower limb injuries. This may be as a result of the biomechanics of the throwing action that baseball pitchers use which is seen as more dangerous to the shoulder and elbow (Davis et al 2009) than the pace bowling action which places more strain on the lumbar spine (Ferdinands et al 2009). In both baseball and softball there is no run-up and this may increase forces on the upper body, unlike in cricket pace bowling, where there is a run-up of up to 30m (Bartlett et al 1996). The run-up speed utilised by cricket pace bowlers influences the kinematics and kinetics of trunk lateral flexion, trunk flexion and knee flexion at front foot placement and ball release (Bartlett et al 1996). The influence of the run-up on the trunk, lumbar spine and lower body movement may result in a higher load being placed on the lower body. A shorter run up may impose less

force on the trunk, lumbar spine and lower body during the baseball and softball pitching action, which may explain the lower rate of trunk, lumbar and lower limb injury when compared with upper limb injury in baseball and softball pitchers. However, the specific biomechanics of the cricket pace bowling, baseball and softball pitching actions may be a cause of the unique distribution of injuries according to body area amongst players of each specific sport.

Due to the biomechanics of the bowling action, the trunk and low back are left vulnerable to injury. Lumbar injury, including soft tissue injury, disc pathology as well as pars interarticularis stress fracture, is common in pace bowlers. Foster et al (1989) tested 82 injury free young male fast bowlers between the ages of 15 and 22 years at the start of a cricket season. Eleven percent of the bowlers sustained a symptomatic stress fracture to the low back and 27% sustained a soft tissue injury to the lower back during the cricket season under review. Lumbar pars interarticularis stress fractures on the non-bowling arm side are common in pace bowlers due to the nature of the pace bowling action (Foster et al 1989; Hardcastle 1993; Gregory et al 2004; Ranson et al 2005; Engstrom and Walker 2007).

The consequences of the biomechanics specifically related to the pace bowling action, become clear when we look at studies comparing pars interarticularis stress fractures in pace bowlers with those participants in other sports (Gregory et al 2004; Ranson et al 2005). In a study undertaken by Gregory et al (2004) it was found that a similar percentage of soccer players and cricketers suffered from spondylolysis. However, the pattern of spondylolysis was however different in cricketers than in soccer players. In the cricketers a higher number of incomplete fractures were seen on the left side of the neural arch while in soccer players a much more symmetrical distribution of spondylolysis was found. Soccer players tend to use

either foot to kick a football which is dependent on a variety of spinal movements, while the pace bowlers uses one arm to bowl, thus the pace bowling action is repeatedly performed in an asymmetrical fashion. Although Gregory et al's (2004) sample of 42 cricketers did not specifically include only pace bowlers, only two participants were not bowlers and only one was a spin bowler (Gregory et al 2004). Similar findings were established in a study undertaken by Ranson et al (2005) which included 36 fast bowlers who were free from low back pain. They also included a control group consisting of soccer players, rugby players, weight lifters, swimmers and athletes participating in general cardiovascular exercise. They found that 81% of the fast bowlers had lumbar pars interarticularis defects on the non-dominant side while only 36% of the control group suffered defects on the non-dominant side. The athlete's body thus seems to adapt to the demands of the specific sport in which an athlete participates.

Not only do the demands of the sport, namely the pace bowling action, put strain on the bony structures but strain is also placed on the lumbar discs. Disc abnormalities were studied by Ranson et al (2005) and they found that 61% of fast bowlers and 53% of controls suffered from disc abnormalities as investigated by Magnetic Resonance Imaging (MRI) scan. Although the prevalence of these abnormalities is very similar, fast bowlers suffered from severe degeneration and a much higher rate of multi-level abnormalities than a control group.

Although the link between low back kinematics and kinetics, and low back injury has been studied intensively in cricket fast bowlers, a clear link is thought to exist between low back kinematics and kinetics, and lower limb injuries (Putnam 1993). Kulas et al (2010) found that added trunk loads resulted in increased knee anterior shear and muscle forces depending on the adaptation strategy of the trunk. Due to the interconnectedness between the spine and the

lower limb, kinematic variables affecting the spine, will also affect the load placed on the lower limb (Zazulak et al 2007a; Kulas et al 2010) with subsequent risk of injury (Nadler et al 2002). The interdependent mechanical interactions in a linked segment system such as the system of motion of the low back can be caused by movement coordination patterns in other body segments (Putnam 1993).

2.4 Traumatic and Non-Traumatic Injuries

The interrelationship between traumatic, acute injury and extrinsic factors; and between non-traumatic, over-use injury and intrinsic factors are explained in this section.

Hagglund et al (2013) differentiated between traumatic and non-traumatic injuries by using the following description: "Injuries with a sudden onset and known cause are categorized as traumatic, and those with a gradual onset and no known trauma are considered overuse injuries." Stretch and Raffan (2011) defined an acute injury as an injury of "rapid onset" and a chronic injury as an injury that involved "prolonged or extended onset".

The two definitions used in these two studies indicate that injuries of sudden onset or acute injuries are associated with traumatic causes, while injuries of gradual onset or chronic injuries are associated with non-traumatic causes. Chronicity may however also result from an acute injury that fails to heal within an acceptable timeframe, therefore the term "over-use injuries" may be more appropriate as described in Engebretsen et al's (2010) definition. "Acute injuries are defined as injuries with a sudden onset associated with a known trauma, whereas overuse injuries are those with a gradual onset without any known trauma" (Engebretsen et al 2010). Meeuwisse (1994) also divided injuries into two broad categories

namely acute injuries associated with a macro-traumatic event (fracture or ligament sprain due to external force, e.g. tackle) and overuse injuries associated with micro-trauma (stress fractures or tendinitis due to overuse). Therefore, for purposes of this study, a traumatic injury is described as an injury that was caused by a traumatic event for example being hit by a ball or slipping on an uneven surface. And a non-traumatic injury is an injury that started with no apparent cause.

Both, traumatic and non-traumatic injuries are sustained by cricketers. In Stretch and Raffan (2011) and Stretch et al (2009) traumatic causes of injury like sliding for the ball and impact by the ball, accounted for the majority of injuries sustained during fielding. Conversely, injuries sustained during the bowling action are mostly non-traumatic and in the majority of cases is of "gradual onset" due to the nature of the pace bowling action and due to over-bowling. It has been shown in many studies investigating the pace bowling action, that injuries sustained by pace bowlers, as a result of the bowling action, are due to the nature of the bowling action (Foster et al 1989; Bartlett et al 1996; Portus et al 2004; Ferdinands et al 2009; Stuelcken et al 2010; Johnson et al 2012) rather than due to traumatic events as in the case of fielding.

2.5 The Interrelationship between Intrinsic and Extrinsic Factors

The following section aims to explain the link between intrinsic factors, extrinsic factors and injury. An intrinsic factor is a factor that comes from within an athlete (person-related), such as flexibility and strength, while an extrinsic factor is a factor that occurs in the athlete's environment such as time of game, player position or exercise load (Meeuwisse 1994; Dvorak and Junge 2000; Orchard 2001; Orchard et al 2001; Cross et al 2013). A combination

of extrinsic and intrinsic factors predisposes an athlete to injury and they are therefore interdependent.

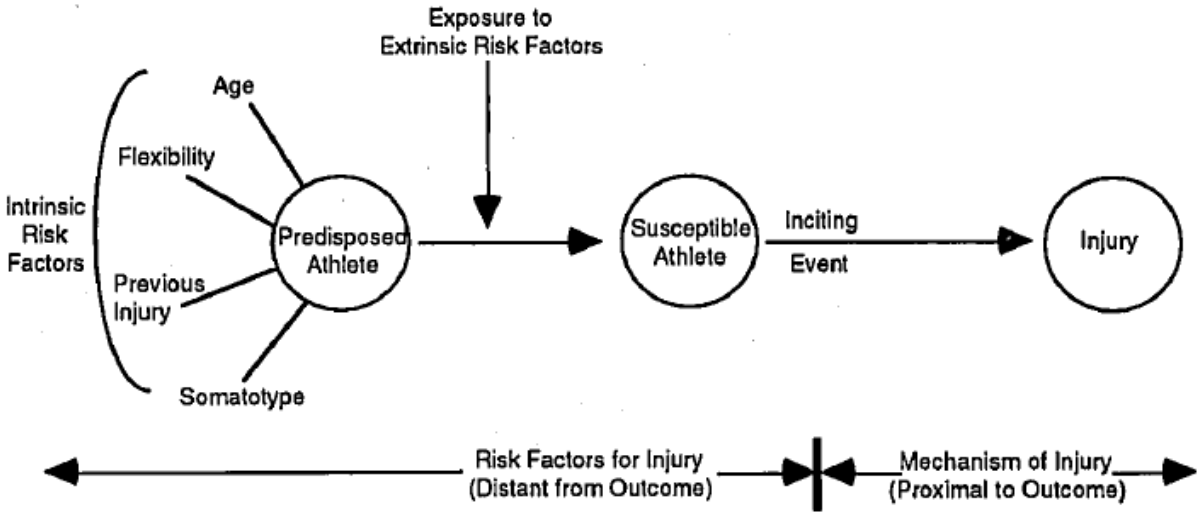


Figure 1. A multifactorial model of athletic injury (Meeuwisse 1994)

Meeuwisse (1994) explained the interrelationship between intrinsic and extrinsic factors by means of a diagram (Figure 1). Intrinsic factors predispose the bowler to injury while the bowler is exposed to extrinsic factors in the presence of these intrinsic predisposing factors. These factors together interact effectively to make the bowler "an accident waiting for a place to happen" (Meeuwisse 1994). Although attention is mostly paid to the inciting event ("the last straw"), like an ankle sprained due to bad pitch conditions, it is important to look at the factors more distant to the injury as well.

It is thus difficult to ascertain if an injury that resulted from an extrinsic cause, like spraining an ankle due to stepping on an uneven surface was purely due to the extrinsic cause (the uneven surface). The extrinsic factor cannot be considered in isolation apart from the intrinsic factors, because better ankle proprioception may have prevented the ankle sprain from occurring. In overuse or non-traumatic injuries there is likely to be a larger contribution of

intrinsic factors. Intrinsic factors (for example poor lumbar proprioception) may predispose a bowler to injury while extrinsic factors (such as bowling second, batting first) may make him more susceptible to injury which both lead to an inciting event (like lumbar muscle strain after an abnormally large number of overs were bowled during a practice session). The inciting event should thus be viewed in the light of the intrinsic and extrinsic risk factors. A different weighting of the different factors may be given depending on the type of injury sustained. Acute injuries for example may place much emphasis on the inciting event and less on the intrinsic factors while overuse or non-traumatic injury may place more emphasis on the intrinsic predisposing factors (Meeuwisse 1994).

The nature of the bowling action is seen as an intrinsic and simultaneously as an extrinsic factor. The inherent nature of the bowling action can be regarded as an extrinsic factor as it is imposed on the bowler as part of the game and it contains certain elements designed for maximal performance which are required by the rules of the game. The pace bowling action can also be regarded as a combination of dangerous intrinsic factors as there are biomechanical and technique-related components which may predispose the bowler to injury.

Injury prevention research and programmes should focus on both extrinsic and intrinsic factors. The following section will examiner literature investigating extrinsic as well as intrinsic factors and how these factors relate to injury. The focus of this section will however be placed on intrinsic factors since they are the major theme of the current thesis.

2.6 Extrinsic and Intrinsic Factors Associated with Injury

Two of the injury-related risk factors most studied amongst pace bowlers are bowler workload (Foster et al 1989; Dennis et al 2003) and the biomechanics of the pace bowling technique (Foster et al 1989; Elliott et al 1992; Ranson et al 2008; Ferdinands et al 2009; Stuelcken et al 2010; Wormgoor et al 2010). Bowler workload is an extrinsic factor. Although the major focus of this thesis is on intrinsic factors, an overview of extrinsic factors are included in the next section.

2.6.1 Extrinsic Factors

Various extrinsic factors which are known to be related to injury in cricketers have been studied and will be mentioned in this section with the aim of showing the importance of incorporating both extrinsic and intrinsic factors in injury prevention programmes. Various suggestions that have been made concerning the modification or elimination of certain extrinsic risk factors are also included in this section.

A high bowling workload has been linked with a higher risk of injury in pace bowlers. In match situations bowlers may be required to bowl four to 10 overs per day in limited over cricket, while they may bowl up to 20 overs a day during the longer version of the game (Stretch and Raffan 2011). Foster et al (1989) found that bowling too many overs in a single spell, or bowling too many spells may increase the pace bowler's risk of sustaining a low back injury. Dennis et al (2003) found that an overextended bowling workload as well as an uncommonly low bowling workload is associated with injury risk. They found that bowlers who bowled fewer than 123 deliveries per week (RR = 1.4, 95% CI 1.0 to 2.0) and those who

bowled more than 188 deliveries per week (RR= 1.4, 95% CI 0.9 to 1.6) were at increased risk of injury.

In a review by Finch et al (1999), various extrinsic factors to prevent cricket injuries were discussed. Primary (pre-event) countermeasures included footwear, nutrition and the playing environment. Secondary (event) countermeasures included protective equipment and surface status; while tertiary (post-event) countermeasures included prompt first aid and access to rehabilitation.

Orchard et al (2002) identified that the major extrinsic factors for bowling injury are a high number of match overs bowled in the previous week, number of days of play and bowling second (batting first) in a match. The authors suggested that the most important potentially reversible risk factor is bowler workload. They further suggested that by allowing bowlers to warm up before the start of the second innings, after batting first, injuries may also be prevented. Other extrinsic factors have also been suggested as predisposing the bowler to injury. Mansingh et al (2006) commented in their discussion that training intensity, recovery technique and lack of accessibility to medical personnel, may constitute extrinsic factors related to the development in pace bowlers. Stretch and Raffan (2011) suggested that extrinsic factors, such as unfamiliar climate and underfoot conditions, and different food and beverage intake, may also influence the risk of injury.

Suggestions that have been put forward to decrease excessive bowling workload include the reduction or elimination of back-to-back games, the institution of a forced off-season, rule changes allowing the 12th man to bowl for an injured player, enforcing the follow-on in test matches and deliberate rotation of bowlers (Orchard et al 2006). Not all these ideas to control

extrinsic injury risk factors are feasible as they may impact on the nature of the game of cricket, as well as its associated tactics and ethics. Despite such difficulties concerning the ability to limit the effect of extrinsic factors on injury, it is possible that an alternative strategy to optimise intrinsic factors with the ability to prevent injury may exist. In doing so, the bowler can be protected against injury in the presence of the imposed extrinsic factors.

2.6.2 Intrinsic Factors

Intrinsic risk factors predisposing the pace bowler to injury have been investigated in recent times. Some authors have conducted cross-sectional studies in which associations between injury and intrinsic risk factors were established (Elliott et al 1992; Portus et al 2004; Stuelcken et al 2008b; Stuelcken et al 2008a; Stuelcken et al 2010), while others performed prospective studies in which the baseline status of intrinsic factors were measured and the incidence of injury were monitored prospectively (Foster et al 1989; Dennis et al 2008). Factors showing statistically significant associations with injury and the identification of factors that can predict injury, provide an opportunity for such factors to be included in injury prevention programmes, and the effectiveness of such programmes to be verified via appropriate research methodologies (McBain et al 2012b).

Intrinsic, strength-related factors, such as shoulder depression and horizontal flexion strength for the preferred limb and quadriceps power in the non-preferred limb are also significantly related to back injuries in fast bowlers (Foster et al 1989). Not only upper limb but also lower limb-related intrinsic factors are known to be associated with injury. A prospective study by Dennis et al (2008) aimed to identify the risk factors of injury in cricket fast bowlers. They found two intrinsic factors that may predict micro-trauma injury to the back, trunk and lower limb in fast bowlers. Their findings concluded that bowlers with a hip internal rotation range

of motion of ≤30˚ on the leg ipsilateral to the bowling arm were at a significantly reduced risk of injury compared with bowlers with >40˚ of rotation. Moreover, bowlers with ankle dorsiflexion lunge of 12.1–14.0 cm on the leg contralateral to the bowling arm were at a significantly increased risk to bowlers with a lunge of >14 cm. Associations between intrinsic factors and low back dysfunction were established by Elliott et al (1992) and Stuelcken et al (2008a). Poorer hamstring or low back flexibility were associated with lumbar disc abnormalities (Elliott et al 1992) while Stuelcken et al (2008a) found that female fast bowlers with low back pain had less lumbar lateral flexion range of motion towards the bowling arm side.

In a systematic review, Morton et al (2013) included muscle architecture as a potential risk factor for low back injury in cricketers. They found inconclusive evidence on the relationship between quadratus lumborum (QL) asymmetry and lumbar bone stress injuries. Muscle imbalance, in particular hypertrophy of the contralateral QL muscle, is associated with lumbar stress fractures (Engstrom et al 2007). However, Kountouris et al (2012) found no significant difference in QL asymmetry in pace bowlers with lumbar spine bone stress injury and those without injury or those with only lumbar soft tissue injury. Different criteria to include MRI's were used by these two studies. Additionally, in Engstrom et al's (2007) study, pace bowlers were followed up for four years, while in Kountouris et al's (2012) study, pace bowlers were followed up over one cricket season. In support of Kountouris et al's (2012) study, De Visser (2007) established in a mathematical model that QL asymmetry is not the cause of stress fractures and may even act to reduce the stress on the lumbar spine during extreme postures and muscle activation. Caution should be applied in the interpretation of mathematical models due to the number of assumptions made in the creation of mathematical models. In another study by Kountouris et al (2013) it was found that pace

bowlers who did not sustain a low back injury during the season under review, had larger QL asymmetries than bowlers who did sustain a low back injury. It is furthermore postulated that a large QL asymmetry may be an indication that the pace bowler is utilising an extreme lateral flexion posture concurrent with large lateral flexion moment in the direction of the non-dominant side (Crewe et al 2013a), which may indicate the need for bowling technique modification.

In addition to physical intrinsic factors, various authors have also established biomechanical intrinsic risk factors for injury. These risk factors are discussed in Section 5.3 ("The Pace Bowling Action and Injury") of this literature review.

The contribution of intrinsic and extrinsic factors on injury rates has also been investigated amongst other populations. In a review undertaken by Dvorak and Junge (2000) associations between football injury and joint stability, muscle strength, tightness, asymmetry, and biomechanics were found. Intrinsic factors associated with non-traumatic injury in football players included eccentric isokinetic ankle flexion strength asymmetries (Fousekis et al 2012). Orchard et al (2001) investigated intrinsic risk factors for anterior cruciate ligament injuries in Australian Rules football players. They found that increased age as well as increased weight and body mass index were significantly associated with injuries. A study on intrinsic factors amongst male military officer cadets showed that those cadets who presented with lower plantar flexor strength and increased dorsiflexion excursion were at a greater risk of Achilles tendon overuse injury (Mahieu et al 2006). Male physical education students are at a high risk of inversion ankle sprains when the following intrinsic factors are present: slower running speed, less cardiorespiratory endurance, decreased balance ability, decreased dorsiflexion muscle strength, decreased dorsiflexion range of motion, less

coordination, and faster reaction of the tibialis anterior and gastrocnemius muscles (Willems et al 2005). In another study on physical education students, Witvrouw et al (2001) found that poorer flexibility of the quadriceps and hamstring muscles may contribute to the development of patellar tendinitis.

Some of the intrinsic risk factors associated with injury as found in other sports or populations may also be associated with injury in cricket pace bowlers. These factors may give a clue as to which intrinsic factors to include in pace bowler specific studies. The identification of intrinsic injury risk factors will add an understanding of the aetiology of injury and in the end assist in the development of evidence based injury prevention programmes.

3. Performance: Ball Release Speed and Accuracy

The pace bowler's performance, in terms of speed and accuracy, is crucial to a team's performance. The faster the bowler delivers the ball to the batsman, the more difficult it becomes for the batsman to play the ball due to reduced reaction time. Not only speed, but also accuracy are key to bowling performance as the bowler aims to bowl the ball strategically in a certain pre-planned area where it is challenging for the batsman to play the ball.

Pace bowlers are bowlers who bowl at a speed of 120km/hr and faster. Speed is measured with a radar gun (Portus et al 2000; Glazier et al 2000; Pyne et al 2006; Duffield et al 2009; Phillips et al 2012) or via kinematic analysis (Portus et al 2004). Frost and Chalmers (2012)

used the following classification system to classify right and left arm pace bowlers according to bowling speed (Table 2):

Table 2. Pace Bowler Classification based on Ball Release Speed

Player type	**Primary Skill Definition**
Right arm medium bowler	Bowls medium pace, 120–130 km/h
Left arm medium bowler	Bowls medium pace, 120–130 km/h
Right arm medium fast bowler	Bowls medium fast pace, 130–140 km/h
Left arm medium fast bowler	Bowls medium fast pace, 130–140 km/h
Right arm fast bowler	Bowls fast pace, >140 km/h
Left arm fast bowler	Bowls fast pace, >140 km/h

For research purposes bowling accuracy is conventionally measured by using targets in different areas, either behind the stumps or on the pitch (Portus et al 2000; Roca et al 2006; Duffield et al 2009; Stuelcken et al 2010; Zhang et al 2011; Phillips et al 2012).

A variety of technique-related three dimensional kinematic variables inherent in the pace bowling action are related to ball release speed. These kinematic factors are described in Section 5.4 ("The Pace Bowling Action and Performance") of this literature review.

Various anthropometric and strength-related variables are also related to ball release speed. Increased shoulder to wrist length as well as total arm length are associated with higher ball release speeds (Glazier et al 2000). This may link with the higher ball release height (Glazier et al 2000). Pyne et al (2006) found that arm length as well as static jump correlated positively with faster ball release speeds. The static jump is performed as a one-legged vertical jump to measure the lower body isoinertial strength. The higher the jump with a 9kg barbell positioned across the shoulders, the higher the ball release speed during pace bowling.

Larger chest and body composition also have been shown to be related to higher ball release speeds (Portus et al 2000). Furthermore it has been found that the angle at which peak torque is generated during shoulder internal and external rotation is correlated with higher ball release speeds (Loram et al 2005), while Wormgoor et al (2010) found that greater shoulder extension strength contributed significantly to higher ball release speeds.

All of the above intrinsic factors related to performance are of the utmost importance to the competitiveness of the pace bowler. Extrinsic factors should be optimised to ensure an ideal environment in which bowlers can perform while the optimisation of intrinsic factors should seek to incorporate these factors into training and technique modification programmes. Where possible, intrinsic factors associated with better performance as well as with the prevention of injury, should be optimised in the pace bowler. In this way the pace bowlers' needs will be met which include both performance as well as an injury free state.

4. Intrinsic Factors Investigated in this Thesis

In this thesis only a small subset of the infinite number of possible intrinsic factors that could be used to describe a pace bowler were investigated. Static and dynamic balance, lumbo-pelvic movement control, knee and lumbar proprioception, and abdominal muscle thickness and activity were chosen as these factors have been associated with either injury or performance in other sports. This section will review the literature on these factors and their association with injury and performance.

4.1 Static and Dynamic Balance

Balance, sometimes used interchangeably with the term, postural control, is defined as the ability to keep the body's centre of mass within the limits of the base of support (Shumway-Cook and Woollacott 2007; Pfusterschmied et al 2013). Winter et al (1990) describes static balance as the ability to maintain a base of support with minimal movement, and dynamic balance as the ability to perform a task while maintaining a static position. Organisation of sensory information may be most important in static balance, while lower limb flexibility, strength and coordination may be more important in dynamic balance (Plisky et al 2006; Gribble et al 2007).

During functional tasks and sports activities, it is important to maintain body stability during static positions as well as during dynamic movements. Superior balance ability is likely to be important during the pace bowling action due to its high load, dynamic and asymmetrical nature.

4.1.1 The Relationship between Balance and Injury

The importance of optimal balance ability in the bowling action is emphasised by the known relationship between poor balance and a higher incidence of injury, as well as the relationship between a highly developed balance ability and the reduced incidence of injuries (Emery et al 2005a; Emery et al 2005b; McGuine and Keene 2006; Herrington et al 2009; Granacher et al 2010).

Herrington et al (2009) tested the dynamic balance of patients with and without anterior cruciate ligament deficiencies. The patients with anterior cruciate ligament deficiencies

performed worse in the star excursion balance test (SEBT) than their healthy counterparts. Balance ability is different in musculoskeletal injury compared to injury free individuals. Furthermore, improvement in balance ability can also be successfully used in the protection against injury. A study by McGuine and Keene (2006) amongst 665 high school basketball and soccer players aimed to prevent the incidence of ankle sprains. The intervention consisted of a five week balance training programme which consisted of balance exercises on different surfaces (floor and wobble board), with and without visual input, and with and without one of the limbs moving. They found that at the end of the season the rate of ankle sprains was significantly lower for subjects in the intervention group. While McGuine and Keene (2006) investigated the effect of a five week balance training programme on the incidence of ankle injuries specifically, Emery et al (2005b) found that a six week balance training programme reduced sports injuries in general. Similarly Plisky et al (2006) found that a decrease in reach distance as established by the SEBT predicted lower limb injury in basketball players. Emery et al (2005c) and Emery et al (2007) showed that a balance training programme using a wobble board had a clinically significant protective effect in reducing sports injuries of all kinds amongst healthy adolescents. Static and dynamic balance training, as an intrinsic factor, may thus possibly be incorporated into injury prevention programmes as it has the potential to optimise the prevention of injury in the pace bowler.

4.1.2 The Relationship between Balance and Athletic Performance

Balance ability adapts to the demands of the sport that the athlete is participating in (Bressel et al 2007). Bressel et al (2007) show that both static and dynamic balance similar in gymnasts and soccer players, but that basketball players displayed inferior static balance compared to gymnasts and inferior dynamic balance compared with soccer players. They suggested that the differences in balance may be due to the unique sensorimotor challenges

imposed by each sport. The change in balance due to the neural adaptation in the somatosensory, visual and vestibular system takes place in accordance to the specific needs of the sport. The improved neural adaptation may be as a result of enhanced fusimotor firing rate, increased motor neuron excitability and increased levels of descending neural pathways as well as decreased neural inhibition (Kakuda et al 1997; Pedersen et al 1998; Aagaard 2003; Bouillon et al 2009; Jakobsen et al 2011). Studies assessing the effect of static and dynamic balance training on sports specific performance, including cricket, are lacking however. Knowledge of the effect of balance training on ball release speed and bowling accuracy in pace bowlers may provide the opportunity for balance training to be included into effective injury prevention and performance optimisation programmes.

4.1.3 The Single Leg Balance Test (SLBT)

The single leg balance test (SLBT) is commonly used in the clinical arena because it is easily performed, user-friendly and requires no equipment other than a stopwatch. In the clinical arena, access to gold standard stabilometry equipment like the force plate is most of the time not possible (Clark et al 2010).

Clark et al (2010) performed the SLBT by getting participants to stand on one leg for 10 seconds. The examiner notes and stops the test if the participant's one leg touches the other, they lift their hands from their hips, they move their stance foot, the contralateral foot touches the floor or they open their eyes. The SLBT is also tested with and without visual input, as the removal of visual input increases the difficulty of the task, which is observed as an increase in the postural sway (centre of pressure speed and range) when measurements are done on a force plate (Hazime et al 2012). At the same time, surfaces of different stability are

used to make the test more difficult, for example, using a wobble board or foam pad (Emery et al 2005b; Emery et al 2007).

Although the SLBT test is often used clinically, poor test-retest reliability (k=0.21) was found for the SLBT, but good intra-rater reliability (k=1.00) (Clark et al 2010). This indicates that the SLBT cannot be used as a reliable clinical measure of improvement in balance or risk of injury.

4.1.4 The Star Excursion Balance Test (SEBT)

The SEBT is an inexpensive and quick method for measuring balance clinically as no expensive equipment is needed. The SEBT requires strength, flexibility, coordination and balance (Plisky et al 2006; Filipa et al 2010). The SEBT can be used to screen athletes for risk of injury (Plisky et al 2006), to assess dynamic balance post-injury and to monitor progress during rehabilitation (Filipa et al 2010). For an illustration of the SEBT refer to Figure 2.

The original SEBT consisted of a grid of eight lines in different directions where the target line is 45˚ from the adjacent line (Gribble et al 2007; Hale et al 2007). It was modified to three reach directions and reliability was established by Plisky et al (2006) (Figure 2).

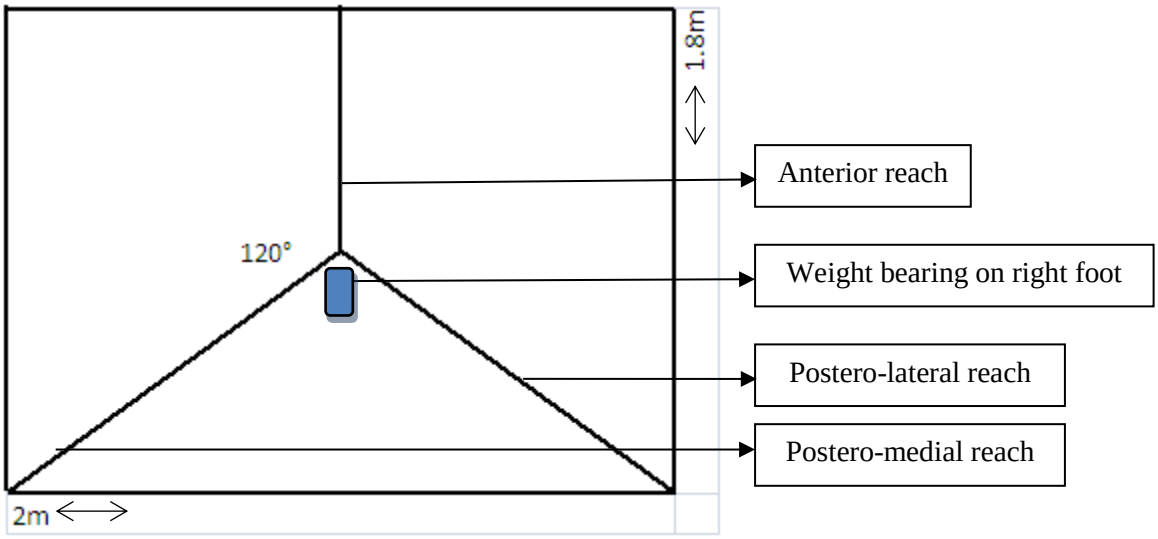


Figure 2. Star Excursion Balance Test (SEBT) mat.

The test-retest reliability is much better in the SEBT than that of the SLBT (ICC 0.98 and k=0.21 respectively) (Clark et al 2010). Inter-rater reliability is excellent for the SEBT (ICC 0.91) (Clark et al 2010). The fact that the SLBT and SEBT do not show a strong association between results suggests that different components of stability are tested (Clark et al 2010). Plisky et al (2006) established the intra-rater reliability for all three reach directions as between 0.84 and 0.87 (ICC) and the test-retest reliability as between 0.89 – 0.93 (ICC).

4.1.5 The Effect of Training Programmes on Balance

A balance training programme aimed at improving balance via wobble board exercises improved reach distances in the SEBT (Fitzgerald et al 2010). Participants improved in the SEBT which may indicate that it is a good tool to assess response to training. The SEBT reach distances also improved after an eight week neuromuscular training programme (Filipa et al 2010) consisting of whole body strength training and core stability training. The neuromuscular training programme was based on injury prevention research. Comparing three groups of middle aged women doing four weeks of standard, strength cycle ergometry

and a control group doing no specific activity showed that the SEBT improved in the cycle ergometer groups (Bouillon et al 2009). This suggests not only strength but also a combination of strength and aerobic activity, specifically cycle ergometry, improved balance. It seems that both balance specific and non-specific exercise or training improves the SEBT.

There is an improvement in the SEBT in chronic ankle instability with a four week neuromuscular training programme consisting of range of motion, strength, neuromuscular control and functional tasks (Hale et al 2007). As the SEBT requires different components including strength, flexibility and coordination (Plisky et al 2006), a programme incorporating these aspects will improve the SEBT reach distances. They also found a difference in reach distance between the involved and uninvolved limbs in participants with chronic ankle instability. This suggests that injury plays a role in reach distance. When participants were standing on the force plate on the involved limb, center of pressure velocity was higher with eyes closed than with eyes open (Hale et al 2007). This highlights the importance of vision in neuromuscular control. Training programmes improve reach distances in the SEBT which shows that balance is a modifiable intrinsic factor with the potential to prevent injury and improve performance in pace bowlers.

4.2 Lumbo-Pelvic Movement Control

This decrease in control of movement is described as the lack of ability to actively control or prevent a compensatory movement when required or instructed to do so (Comerford and Mottram 2001a; Comerford and Mottram 2001b).

Comerford and Mottram (2001a; 2001b) have developed a theoretical model which states that functional stability is dependent on integrated local and global muscle function. One example of the effect of local muscle dysfunction is that if the mono-articular, weak local muscles, such as the transverses abdominus (TA) and lumbar multifidi (LM), are unable to control the movement and excessive segmental motion occurs over a specific joint, local hypermobility, tissue pathology and pain is likely to result (Comerford and Mottram 2001a; Comerford and Mottram 2001b). At the same time flexibility of the surrounding joints and soft tissue is crucial to allow for optimal movement to occur (Sahrmann 2002). Although extensive research is still needed to develop this theoretical model into evidence, it may serve as an explanation of how movement dysfunction can predispose the pace bowler to injury. Specific to cricket pace bowlers, overloading the spine with high load forces during bowling in the presence of uncontrolled movement and muscle imbalance further predisposes bowlers to injury (Roussel et al 2009).

One of the theories concerning lumbo-pelvic movement control, namely relative flexibility (Sahrmann 2002; O'Sullivan 2005), suggests that movement follows the pathway of least effort, for example, if the hip flexors are stiff then a hip extension movement is likely to occur in the low back, which may lead to increased movement in the low back and in the end segmental instability. Movement control should thus be evaluated keeping in mind relative flexibility as well as muscle activation. The basic principle for this line of reasoning is that the proximal component, e.g. the lumbar spine, should be kept stable while the distal segment, e.g. the leg, moves (Jull et al 1993) by activation of the core muscles. The core, which consists of the diaphragm, abdominal, paraspinal, pelvic floor and hip muscles, is responsible for proper force distribution and maximal force generation, causing minimal

compressive, translational and shearing forces on joints in the kinetic chain (Akuthota et al 2008).

4.2.1 The Relationship between Lumbo-Pelvic Movement Control and Injury

The lumbo-pelvic movement control tests have the ability to distinguish between patients with and without non-specific low back pain. Luomajoki et al (2008) established very good discriminant validity of six lumbo-pelvic movement control tests, namely the waiter's bow, pelvic tilt, one leg stance, sitting knee extension, rocking forwards and backwards, and prone lying knee extension. In their study, patients suffering from low back pain had a significantly higher number of positive lumbo-pelvic movement control tests than those without low back pain ($p<0.001$). These results indicate that movement control tests can be used to diagnose low back dysfunction in patients. Similar results were found by Luomajoki et al (2009).

Only two studies could be found that investigated the ability of lumbo-pelvic movement control tests to predict injury (Zazulak et al 2007a; Roussel et al 2009). Roussel et al (2009) in a prospective study, found that two lumbo-pelvic movement control tests, the knee lift abdominal test (KLAT) and waiter's bow (WB), were associated with increased risk of developing lower limb or lumbar spine injuries in dancers. In dancers the passive subsystem has traits of hypermobility (Panjabi 1992a) which results in altered lumbo-pelvic movement control and subsequent compensation in movement in the lower limbs, leading to injury. In other prospective studies, Zazulak et al (2007a; 2007b) found that impaired core stability predicted knee injury in female athletes. Again the balance between flexibility and core strength may be the components playing a role in the loss of lumbo-pelvic movement control and subsequent injury.

4.2.2 The Relationship between Lumbo-Pelvic Movement Control and Athletic Performance

The association between lumbo-pelvic movement control tests as described in Section 4.2.3 ("Lumbo-Pelvic Movement Control Tests") and sports performance have not yet been established. In cricketers, this data will allow for lumbo-pelvic movement control tests to be used as screening tests to predict injury and performance.

4.2.3 Lumbo-Pelvic Movement Control Tests

Various lumbo-pelvic movement control tests were developed by, amongst others, Van Dillen et al (1998), Luomajoki et al (2008) and Sahrmann (2002). Illustrations of these tests are shown in Chapter 2, Section 1, Table 1.

Luomajoki et al (2007) aimed to establish the inter-rater and intra-rater reliability of the lumbo-pelvic movement control tests. The inter-rater agreement (kappa coefficient) of five of the lumbo-pelvic movement control tests showed substantial agreement (k=0.6-0.8) [WB, dorsal tilt of the pelvis (DTP), one leg stance left (OLS L), sitting knee extension (SKE), rocking forward (RF)], four tests showed good agreement (k=0.4-0.6) [one leg stance right (OLS R), rocking backwards (RB), prone knee bend extension, prone knee bend rotation] and one test showed fair agreement (k<0.4) between testers [crook lying hip abduction/lateral rotation (BKFO)]. The intra-rater reliability showed excellent reliability (k>0.8) in five tests (WB, DTP, OLS L, SKE, crook lying hip abduction/lateral rotation), substantial reliability (k=0.6-0.8) in four tests (OLS R, RB, prone knee bend extension, prone knee bend rotation) and good reliability (k=0.4-0.6) in one test (RF) (Luomajoki et al 2007).

Roussel et al (2009) established the inter-rater reliability for the BKFO, KLAT and the standing bow (also called the WB). Based on the pressure biofeedback unit pressure recordings the intra-class correlation (ICC) was between 0.61 and 0.91 for the BKFO and above 0.85 for the KLAT. Substantial agreement was found for the WB (k=0.6-0.8).

The reliability as well as discriminative validity of the lumbo-pelvic movement control tests has been established which makes these tests appropriate outcome measures to use in the assessment of movement control in a specific sports population.

4.3 Proprioception

Proprioception is defined as the sensation of joint movement (kinesthesia) and joint position (Anderson et al 2005; Angoules et al 2011). Proprioceptive input is derived from muscle, joint and skin receptors in a complex interaction between afferent and efferent receptors (Gandevia et al 1992; Newcomer et al 2000a).

4.3.1 The Relationship between Proprioception and Injury

The link between decreased proprioception and peripheral joint injury has been established (Forwell and Carnahan 1996). Forwell et al (1996) found that patients diagnosed with recurrent glenohumeral instability, suffer from a proprioceptive deficit while Arockiaraj et al (2013) found significant proprioceptive differences in patients with anterior cruciate ligament deficient knees compared with healthy controls. They also found that there was no significant difference between the proprioception of the knee that sustained the anterior cruciate ligament injury and the uninjured knee. This may suggest that the insufficient proprioception may have been a cause of injury and not the results of injury. Both these studies found that a

decrease in proprioception, specifically joint position sense, is associated with injury. In the studies done by Forwell et al (1996), Arockiaraj et al (2013) as well as by O'Sullivan et al (2003) it is emphasised that the presence of pain, but also the presence of joint instability, is associated with poor proprioception.

Not only peripheral joint injury, but also lumbar dysfunction is associated with decreased proprioception. O'Sullivan et al (2003) found that lumbar repositioning error was significantly greater for a group diagnosed with lumbar spine instability and associated chronic low back pain than for the pain free group. They tested participants' ability to reproduce a neutral spinal posture during sitting. While the findings of O'Sullivan et al (2003) are related to a specific population, Georgy (2011) confirmed this difference in proprioception in two other low back pain populations. Lumbar position sense was evaluated by Georgy (2011) in healthy participants, patients with non-specific mechanical back dysfunction and patients with discogenic back dysfunction. A significant difference in lumbar position sense was found between the healthy participants and the two back dysfunction groups, where the healthy participants performed much better than the back dysfunction groups. There was no difference in position sense between the two non-specific mechanical back dysfunction and the discogenic back dysfunction groups which may suggest that the symptoms shared by these pathologies, like pain and instability, influence proprioceptive function and not the pathology itself (Georgy 2011).

In contrast, no difference in lumbar position sense was found between participants with and without low back pain by Newcomer et al (2000b) while a similar study was repeated by the same authors (Newcomer et al 2000c) with a significant difference between the groups found. In the second study the lower limbs of the participants were restrained as the authors felt that

proprioceptive feedback was received by the lower limbs and not only from the spine, although the measurement device that was used isolated the spinal area between L1 and S1. It is thus unclear if the restraint of the lower limbs was responsible for changes in results. However the weight bearing nature of their measurements is important because the function of the proprioceptors, including Ruffini's endings, Pacinian corpuscles, Golgi-Mazzoni corpuscles, Golgi tendon organs and muscle spindles, is enhanced by weight bearing positions thus increasing the perception of joint position (Bunton et al 1993; Lin et al 2006).

Peripheral as well as spinal pathology may be associated with proprioceptive deficits which may lead to abnormal loading across joint surfaces (Forwell and Carnahan 1996), tissue overload and injury (O'Sullivan et al 2003; Cholewicki et al 2005). However, injury may be both a cause and a consequence of poor proprioception (Parkhurst and Burnett 1994).

4.3.2 The Relationship between Proprioception and Athletic Performance

The link between proprioception and sports performance has been established where joint position sense is able to distinguish elite from novice athletes including tennis players (Lin et al 2006), free-flyers (Pinsault and Vuillerme 2009) and gymnasts (Lephart et al 1996).

Lin et al (2006) used a closed-chain reposition test to compare hip and knee proprioception amongst elite, amateur and novice tennis players. They found that elite players' hip joint proprioception was significantly better than that of the amateurs and novice tennis players ($p<0.167$). Furthermore they found that the proprioception of the hip as well as the knee of the stance-dominant leg of elite players was significantly better than that of novice players ($p<0.0033$). Pinsault and Vuillerme (2009) found a more accurate and consistent head repositioning performance in elite free-flyers than in a group of non free-flyers ($p<0.05$). The

non free-flyers were experts in other sports like soccer, skiing, athletics and swimming. In another study, trained gymnasts had significantly better knee proprioception than healthy non-gymnasts (p=0.011) (Lephart et al 1996). In all three studies it was suggested that these differences in proprioception were as a result of years of sport specific training which developed enhanced neurosensory pathways according to the needs of the sport.

It is thus possible that the demands of a specific sport develop certain neurophysiological pathways better than others. Proprioception includes both neuromuscular and somatosensory components (Rein et al 2011). The somatosensory senses include conscious and unconscious appreciation of proprioception. Conscious (voluntary) control includes kinaesthesia, joint position sense and sense of resistance (Riemann and Lephart 2002). Unconscious (involuntary) control in proprioception is reflected in neuromuscular senses, including posture control, joint stability and muscle reaction times. Neurophysiological pathways for conscious sensory appreciation are associated with the dorsal lateral tracts while the spinocerebellar tracts are responsible for unconscious proprioception (Riemann and Lephart 2002). The proprioceptors may also be utilised differently according to the demands of the sport. Friden et al (1996) suggest that proprioception during slow velocities maximally stimulates joint receptors, while active reproduction tests stimulate both muscle and joint receptors. Ruffini receptors behave as both static and dynamic receptors, while the Pacinian corpuscles are classified as dynamic receptors (Riemann and Lephart 2002). During the bowling action muscle activations take place unconsciously and synonymously take into account requirements of the task, i.e. speed and load. Proprioception i.e. awareness of limb position, joint angles, and muscle tension and length are used in reflexive, automatic and voluntary reactions that are part of the bowling action.

4.3.3 Joint Position Sense Testing

Joint position sense (as a form of proprioception) is the ability to determine where a particular body part is in space (Newcomer et al 2000b; Newcomer et al 2000c). Joint position sense is mainly sensed by muscle spindles, while skin and joint receptors play a supporting role (Proske 2006).

Joint position sense can be tested by joint repositioning or by time to detect passive movement. Joint position sense is tested by positioning a joint in a certain position, then, after removing it from the position for a few seconds, the athlete is requested to position the joint in exactly the same position (the subject perceived target position). Joint reposition error is the difference between the initial position and the replicated position (Lin et al 2006; Pinsault and Vuillerme 2009; Georgy 2011). An alternative method of determining joint position error is to record the time taken to detect motion (Angoules et al 2011; Arockiaraj et al 2013) where the researcher subjects a joint to passive movement and a patient has to report as soon as they perceive a certain joint to be moved.

Joint position sense can be tested by positional detection devices such as the electro-inclinometer (Lin et al 2006), a laser device (Pinsault and Vuillerme 2009), isokinetic dynamometer (Georgy 2011; Angoules et al 2011) and electro-goniometer (Arockiaraj et al 2013).

4.3.4 The Electro-goniometer

A flexible electro-goniometer consists of a thin piece of wire which is sensitive to bending. One end of the wire is positioned on each side of the joint under assessment (Whittle 2007).

The amount of bending changes the output voltage (joint angle) (Richards 2008). The electro-goniometer has previously shown to be reliable (ICC=0.92, p=<0.0001, CI 0.89-0.95) and accurate as compared to a benchmark standard plurimeter (r > 0.99, P < 0.0001) (Perriman et al 2010). Arockiaraj et al (2013) found that the electro-goniometer has a sensitivity of 0.04°/mV and an accuracy of 0.1° which makes it a good tool to use for the assessment of joint position sense.

Joint position sense, as a measure of proprioception, is related to both injury as well as performance in different populations. The further investigation of this intrinsic factor in cricket pace bowlers may lead to additional associations with injury and performance and in the end can form a valuable part of injury prevention studies specific to cricket pace bowlers.

4.4 Abdominal Muscle Architecture

The abdominal musculature plays a protective role against low back injury by increasing the stability of the lumbar segmental vertebrae (Panjabi 1992a; Panjabi 1992b). The assessment of thickness changes via Rehabilitative Ultrasound Imaging (RUSI) of the TA, obliquus abdominis internus (OI) and obliquus abdominis externus (OE) is a validated measure of activity of the abdominal muscles (Koppenhaver et al 2009).

4.4.1 The Relationship between Abdominal Muscle Architecture and Injury

The association between abdominal muscle thickness and pain has been established in various studies (Kiesel et al 2008; Jansen et al 2010; Rasouli et al 2011). Jansen et al (2010) found that athletes suffering from longstanding groin pain had a significantly smaller TA at rest than those free of pain (p<0.001). Furthermore, a difference in thickness percentage

change in TA between participants with and without low back pain exists (Rasouli et al 2011). Thickness percentage change was calculated as muscle thickness during activity as a ratio to muscle thickness at rest (Hodges et al 2003), thus muscle thickness in contracted state minus muscle thickness at rest, divided by muscle thickness at rest times 100 (Teyhen et al 2009). This difference in thickness percentage change increases as the stability of the sitting position decreases, which suggests that as the demands placed on TA increase the ability to meet these demands decreases (Rasouli et al 2011).

The above two studies have been confirmed by Kiesel et al (2008) who found that pain negatively influenced the activation of TA. The TA showed significantly lower activation levels during the abdominal drawing in manoeuvre after pain was induced by injecting 5% hypertonic saline into the longissimus muscle ($p<0.01$). This finding may be linked to the pain-adaptation model where the dysfunction, i.e. decrease in muscle activation, happens as a result of a protective adaptation (Lund et al 1991). Altered lateral abdominal muscle recruitment patterns are present in patients with lumbo-pelvic pain (Teyhen et al 2009). Teyhen et al (2009) investigated the activation of the lateral abdominal wall in patients with uni-lateral lumbo-pelvic pain and found no difference in activation between the symptomatic and non-symptomatic sides. Also, no side to side differences were found in healthy controls. The fact that the TA muscle on both sides are affected although the pathology is present only on one side, shows that pain as a symptom of pathology affects the activation of the abdominal muscles and not necessarily the pathology itself. In a study by Hides et al (2008), cricketers with low back pain showed a reduced ability to contract the TA muscle independently from the other muscles during the abdominal drawing in manoeuvre.

4.4.2 The Relationship between Abdominal Muscle Architecture and Athletic Performance

The lateral abdominal wall presents differently in different athletes probably due to the adaptation as a result of the sport specific demands. Weightlifters have significantly thicker TA and OI muscles than matched controls ($p<0.01$) (Sitilertpisan et al 2011). Sitilertpisan et al (2011) suggest that physiological overload of the muscle due to strenuous training leads to muscle hypertrophy and will result in thicker TA and OI muscles than their age, weight and height matched counterparts.

Studies show that the more active the individual the more pronounced the difference between muscle thickness and activation between the sides of the body (Rankin et al 2006; Springer et al 2006; Mannion et al 2008). Hides et al (2008) found that muscle imbalances in pace bowlers occurred where the OI muscle on the contralateral side to the bowling arm is significantly thicker than the ipsilateral side. The exact mechanism behind the preferential hypertrophy of certain muscles due to sport specific demands should still be investigated. The effect of abdominal muscle thickness as measured by RUSI on performance and injury of these muscular adaptations should be established. Studies investigating the association between abdominal muscle thickness and increased athletic performance are lacking.

4.4.3 Rehabilitative Ultrasound Imaging (RUSI)

RUSI is defined as the use of ultrasound imaging in the basic, applied, and clinical rehabilitative research of neuro-musculoskeletal disorders to inform clinical practice (Teyhen 2011). RUSI is often used as a surrogate measure for activation of the abdominal muscles

(Teyhen 2011). The intra-examiner reliability ranges from 0.85 to 0.99 (ICC) and the inter-examiner reliability ranged from 0.74 to 0.94 (ICC) (Koppenhaver et al 2009; Lariviere et al 2013). The inter-rater reliability for image measurements is 0.96 to 0.98 (ICC). (Koppenhaver et al 2009). It has been found that thickness percentage change as measured by RUSI is well correlated with the same measurements done by using MRI (0.78 to 0.95 ICC) (Hides et al 2006) and by electromyography (EMG) (R^2=0.87) (McMeeken et al 2004).

Abdominal muscle thickness and activation are influenced by the presence of pain. The lateral abdominal wall also adapts in terms of thickness based on the demands of the sport. The assessment of the thickness and activation of the lateral abdominal wall with RUSI are crucial in the search of intrinsic factors impacting on injury and performance in the pace bowler.

5. The Pace Bowling Action

The game of cricket consists of different activities, namely batting, pace bowling, spin bowling, wicket keeping and fielding. The role of the pace bowler is to deliver the ball at a high speed as accurately as possible to the opposing batsman. In this section literature on the phases and classification of the pace bowling action, as well as injury- and performance-related factors associated with pace bowling are reviewed.

5.1 Phases of the Pace Bowling Action

The pace bowling action has been classified as being made up of the following definable phases (Bartlett et al 1996): the run up, the pre-delivery stride, delivery stride (back foot placement, front foot placement and ball release), and follow-through.

The run up starts as the bowler progresses toward the wicket be it walking or running. This phase ends as the bowler leaps into the air, which denotes the start of the pre-delivery phase. The pre-delivery phase starts with a jump of the left foot (reference is made to a right handed bowler) and is completed with a land on the right or back foot. The back foot contact phase (also called the delivery stride phase) takes place from back foot contact until the front foot makes contact with the ground, while the front foot contact phase (also called the power phase) starts with front foot contact and ends at ball release. The follow through is marked by the bowling arm that follows through down the outside of the left thigh, allowing the bowler to reduce speed. An illustration of the pace bowling action can be found in Figure 3.

During the power phase of the pace bowling action, the kinetic forces, including power, torque and ground reaction forces, acting upon the lumbar spine are at their highest level (Foster et al 1989; Ferdinands et al 2009). Due to the high kinetic forces in the power phase, it is also the phase where injury is most likely to be sustained (Ferdinands et al 2009; Stuelcken et al 2010). It is therefore relevant to establish the intrinsic and kinematic variables that occur in the power phase of the bowling action and their relationship to injury.

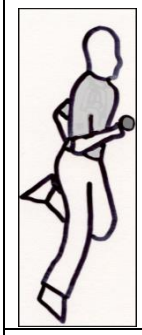
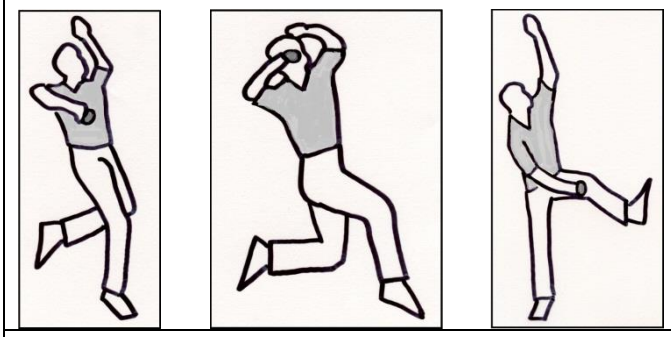
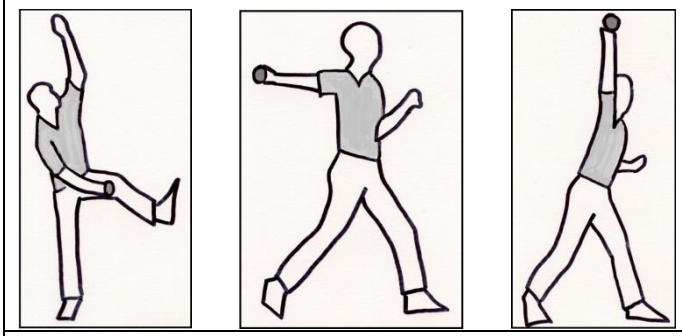
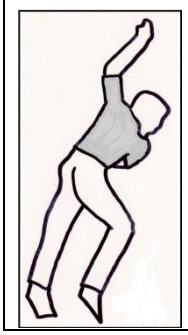
	**Run-up** The bowler walks or jogs, gradually increasing his speed, as he approaches the wicket. The run-up ends as he leaps into the air at the start of the pre-delivery stride. The run-up length varies between 15-30m.
	**The pre-delivery stride** The bowler jumps off his left foot and lands on the right or back foot. The shoulders are pointing down the wicket.
	**The delivery stride** The bowler lands on his back foot with the body leaning away from the batsman. The delivery stride includes back foot strike, front foot strike and ball release.
	**Follow-through** The bowling arm follows through down the outside of the left thigh.

Figure 3 A schematic presentation of the cricket bowling action (Bartlett et al 1996; Ferdinands et al 2009) (reference is made to the right handed bowler)

5.2 Classification of the Pace Bowling Action

The association between bowling action classification and low back injury has been established by researchers (Foster et al 1989; Elliott et al 1992; Portus et al 2004). However, this classification is based on alignment of the shoulders during the back foot contact phase and shoulder counter-rotation during the delivery stride (Portus et al 2004), while the greatest mechanical load on the spine occurs during the power phase (front foot contact phase) (Burnett et al 1998; Ranson et al 2008). Furthermore, just before (Ranson et al 2008) and at commencement of the power phase (Stuelcken et al 2010), no difference in alignment of the thorax relative to the pelvis occurs, which suggests that all bowlers are in roughly the same position before the high load power phase starts regardless of shoulder alignment at back foot impact and the consequent classification as mixed or non-mixed action (Portus et al 2004). Another concern is that shoulder counter-rotation which is used in the action classification of pace bowlers, is an isolated kinematic parameter, is removed from pelvic position, is not an indicator of lumbar torsional load (Stuelcken et al 2010) and is not associated with lower trunk extension, lateral flexion or rotation (Burnett et al 1998; Ranson et al 2008; Stuelcken et al 2010). Although the definition of a mixed action also refers to shoulder-pelvic separation angles, which includes both shoulder and pelvic alignment, this alignment is also established at back foot placement where the spine is in a relatively neutral position and not under a high load (Portus et al 2004; Ranson et al 2008). Recent research found the kinematics of the spine during the front foot contact phase, or power phase, to be associated with injury rather than bowling action classification based on shoulder counter-rotation (Stuelcken et al 2010). Therefore this study investigates the association between injury and spinal angles at front foot placement and ball release, rather than those at back foot placement.

5.3 The Pace Bowling Action and Injury

Bowling-related biomechanical risk factors to injury have been established namely trunk rotation to re-align the shoulders by more than 40˚ to a more side-on position between back foot impact and front foot impact in the delivery stride (Foster et al 1989) as well as a greater ball release height when expressed as a percentage of standing height (Foster et al 1989; Elliott et al 1992). Abnormal radiologic features in the lumbar spine were found in bowlers who make use of a combined front-on back foot placement and a side-on shoulder alignment (Elliott et al 1992). Portus et al (2004) also reported that shoulder counter-rotation was significantly higher in bowlers who reported lumbar spine stress fractures, while the non-trunk injured group displayed a more flexed knee at front foot contact and ball release. Not only shoulder and pelvis rotation in the transverse plane, but also a larger lumbar lateral flexion range utilised during the delivery stride were associated with female fast bowlers suffering from low back pain (Stuelcken et al 2010). Added to the above kinematic risk factors are the high ground reaction forces associated with the power phase - between the front foot placement and ball release components of the pace bowling action (Hurrion et al 2000; Ferdinands et al 2009; Worthington et al 2013). A combination of kinematic bowling related issues as described above and high ground reaction forces may predispose the bowler to injury.

5.4 The Pace Bowling Action and Performance

The relationship between high ball release speeds and technique-related three dimensional kinematics inherent to the pace bowling action have been established. One of the factors that is known to influence bowling speed is the front knee angle at front foot placement and ball release positions during the delivery phase of the bowling action (Elloitt et al 1986; Portus et

al 2004; Loram et al 2005; Crewe et al 2013b). Loram et al (2005) and Portus et al (2004) established that a front knee angle at front foot placement of approximately 160˚ to 164º and at a ball release position 148˚ to 150º of knee extension are more closely related to higher ball release speed than smaller knee angles. One of the reasons why a relatively extended knee is associated with a higher ball release speed is thought to be due to increased height at ball release (Loram et al 2005), thus an increase in the radial distance between front foot contact and the extended bowling arm, results in a greater tangential end point velocity (Bartlett et al 1996). Another reason may be due to the more efficient transfer of kinetic energy to the ball (Portus et al 2004).

Even though it is believed that a more extended knee may contribute to higher ball release speed by increasing ball release height, there is still, however, controversy around the relationship between ball release height and ball release speed (Wormgoor et al 2010). Variables related to shoulder and pelvis position in the transverse plane namely, increased shoulder counter-rotation (Crewe et al 2013b), maximum hip-shoulder separation angle occurring later in the delivery stride (Portus et al 2004), a larger shoulder rotation to ball release (Portus et al 2004) and shoulder alignment in the transverse plane rotated further away from the batsman at front foot strike (Wormgoor et al 2010) was present in the faster bowlers. Portus et al (2000) found that an increase in shoulder counter rotation occurs when bowlers are exposed to multiple overs and this occurrence of shoulder counter-rotation is also negatively correlated to accuracy.

Glazier et al (2000) found that run-up speed as measured at the pre-delivery stride has a positive association with ball release speed. A greater ankle height during the delivery stride (Wormgoor et al 2010) is also correlated with higher ball release speeds.

5.5 The Trade-Off between Higher Ball Release Speeds and Injury Prevention

A clear trade-off is present between optimal performance and injury prevention which is confirmed by Crew et al (2013b) in that a faster ball release speed is associated with increased lumbo-pelvic shear force. One example of this trade-off is that a straighter front knee is associated with increased ball release speed (Portus et al 2004; Loram et al 2005; Crewe et al 2013b), but also with a higher risk of sustaining an injury (Foster et al 1989; Elliott et al 1992) as a more extended knee angle is associated with higher lumbar load (Crewe et al 2013b). Better trunk stability is also associated with a more flexed knee (Portus et al 2000). At the same time, trunk stability (Hilligan 2008) but unfortunately not run-up speed (Bartlett et al 1996) is associated with higher ball release speeds. It should be noted however that not all intrinsic and extrinsic factors act in a way that forces a trade-off between performance and injury prevention. Extrinsic and intrinsic factors related to the promotion of a more "protective" front knee angle and at the same time associated with higher ball release speeds should be further investigated and encouraged amongst bowlers.

5.6 The Kinematic Analysis of the Pace Bowling Action

Biomechanics is the study of mechanical laws and their application to living organisms, especially the human body and its movement (Richards 2008). Kinematics is a subsection of biomechanics and describes the motion of a body without reference to the forces involved (Whittle 2007). Three dimensional positions can be calculated for the light reflective markers fixed to a participant's body segments, as long as they are visible to at least two high speed cameras (Whittle 2007). A three dimensional model can then be reconstructed through the use of specialised computer software which makes video kinematic motion analysis an

objective method to use in the assessment of angles between body segments. An unavoidable limitation of the use of skin markers is that, due to skin movement, the marker movement does not always accurately represent the movement of the underlying structures. On average the measurement error is between 1mm and 3mm (Whittle 2007). The measurement accuracy of a kinematic system can however be improved by increasing the extent of the view of the cameras. Kinematic video motion analysis is appropriate for the analysis of sport-specific activities and was therefore the method of choice in the analysis of the pace bowling action.

6. Conclusion to the Literature Review

The inherent high load nature of the pace bowling action predisposes the pace bowler to injury and therefore the prevalence of especially trunk, lumbar and lower limb injury is high in pace bowlers. Extrinsic factors like bowling workload make the bowler more susceptible to injuries, while intrinsic factors like upper limb horizontal flexion strength predispose the bowler further to injury. Various studies have been done and prevention programmes have been implemented based mainly on extrinsic risk factors. Such research is a positive step towards preventing injuries to pace bowlers and this can be further enhanced by the investigation and incorporation of intrinsic risk factors into the prevention of injuries. Intrinsic factors like shoulder strength are also associated with increased performance namely higher ball release speed. Intrinsic factors associated both with injury prevention as well as with performance should be further investigated and encouraged in pace bowlers. Intrinsic factors like balance, lumbo-pelvic movement control, proprioception and abdominal muscle thickness have been studied for their associations with injury and/or performance in other populations. The tests used to investigate these constructs in the clinical arena are valid and reliable. Intrinsic factors may be optimised with the aim to protect the pace bowler against

injury in the presence of the high load bowling action. The power phase of the bowling action is the phase where highest demands are placed on the body of the pace bowler. Certain technique-related intrinsic factors like a more extended front knee angle are associated with injury, while at the same time this kinematic variable is associated with higher ball release speed. There is thus a clear trade-off between injury prevention and performance present in the pace bowler. This chapter reviewed the literature on injury, performance and intrinsic factors related to pace bowling. The next seven chapters contain original manuscripts showing the relationship between intrinsic factors, injury and performance.

7. Rationale for the Studies Contributing to this Thesis

The intention for conducting and including Chapters 2-7 (Papers 1-6) in this thesis was to make a meaningful contribution to the injury prevention literature, particularly concerning those factors associated with and which may inform practices in injury prevention in the light of the pace bowler's need to optimise performance.

In the subsections hereafter I describe, in more detail, the rationale for the need for research concerning injury prevention, the study of amateur pace bowlers as a study group, as well as the reasoning behind the study of lower back and lower limb injuries, intrinsic factors in pace bowlers, longitudinal assessment of injury and performance data. The rationale section of this thesis then concludes with justification of the need for research into the power phase of the bowling action, the importance of performance centred research and the physical adaptation to the pace bowling action.

7.1 The Need for Injury Prevention

The pace bowling action puts immense strain on the body in the pursuit of optimal performance, especially high ball release speed and bowling accuracy. Injuries in cricket pace bowlers are common and preventative measures have been studied and reported in the literature. Extrinsic prevention methods which include guidelines on bowling workload have been implemented, while intrinsic prevention methods may protect the pace bowler against injury in the presence of the high load nature of the pace bowling action. The studies included in this thesis investigate the association between intrinsic factors including lower limb static and dynamic balance, lumbo-pelvic movement control, lumbar proprioception, knee proprioception, spinal and knee kinematics and their relationship with injury and/or performance. This thesis also contains a study that investigated the consequential and acquired muscle asymmetries typical in the pace bowler. Both injury prevention and performance are of cardinal importance to the pace bowler and are often in a fine balancing act in order for the bowler to obtain a level of optimal performance while at the same time maintaining an intrinsic environment which facilitates injury prevention. Furthermore, in the investigation of injury preventative factors, it is important to study extrinsic factors, technique-related intrinsic factors which prevent injury at the expense of performance; as well as neuromuscular intrinsic factors which prevent injury and at the same time optimise performance. The need for injury prevention in amateur pace bowlers is immense and the studies included in this thesis have been carefully considered as will be explained the subsequent sections.

7.2 The Population of Amateur Pace Bowlers

South African cricketers playing club cricket in the premier league are considered as amateurs. These cricketers are usually employed in their own careers or are students which decreases the amount of time that they have available for training, conditioning and rehabilitation. The coaching team for amateur level cricketers usually consists of a coach and a manager with no team doctor, physiotherapist or biokineticist. This negatively impacts on their access to health professionals' input in comparison with professional cricketers who do have these privileges. Amateur cricketers are likely to be especially vulnerable as injuries occurring during the season may not be rehabilitated properly and subsequently the associations between intrinsic factors and injury may be more apparent. Furthermore, this population is competitive which may contribute to the strong will to perform and at the same time to stay injury free.

Many studies have investigated professional as well as school boy cricketers while studies on amateurs are lacking. Young cricketers between the ages of 13 and 18 years are different to adults in terms of their physiology which impacts on their predisposition to injury and phases of healing. Additionally, these two groups differ in some biomechanical elements of the pace bowling action. It is also thought that young cricketers differ from an adult population in that young pace bowlers who sustain injuries during their bowling career may have given up on the sport by the time they approach adulthood. The composition of the adult pace bowler population group is therefore affected by natural selection which may cause this group to differ from the original population. Caution is thus advised when generalising findings from this young population group to adult pace bowlers which emphasises the need for studies amongst amateur pace bowlers specifically.

7.3 Low Back and Lower Limb Injuries

Pace bowlers sustain the majority of injuries to the low back and lower limbs. Most previous studies focused specifically on low back injuries in pace bowlers, but due to the "interconnectedness" of the low back and the lower limbs as part of the kinetic chain, it was found appropriate to group low back and lower limb injuries together in Chapters 2 and 4. The same definition of injury was used for all three injury-related papers (Chapters 2, 3 and 4) in that musculoskeletal conditions, which resulted in missed training sessions or matches, were identified.

7.4 The Investigation of Intrinsic Factors

The pace bowler utilises intrinsic factors, or person-related factors to attain a high bowling speed. Some of these intrinsic factors may predispose the pace bowler to injury. Intrinsic factors that have not previously been studied in pace bowlers are included in Chapters 2 and 3. Chapters 2 and 3 investigate the link between injury and neuromuscular intrinsic factors, namely lower limb static and dynamic balance, lumbo-pelvic movement control and lumbar proprioception. A relationship was found between injury-related variables, static and dynamic balance, and lumbar proprioception. It is hypothesised that these intrinsic factors may protect the bowler against injury while at the same time optimise performance as a link between these intrinsic factors and performance was found in the literature on other sports. In this thesis the link with injury was established and it is recommended that the same link with performance be established in future studies.

The inclusion of not only neuromuscular intrinsic factors but also technique-related intrinsic factors in this thesis was considered crucial as both types plays a role in injury prevention.

Technique-related intrinsic factors are often associated with injury as well as with faster ball release speeds. Technique-related intrinsic factors are investigated for a relationship with injury (Chapter 4) and performance (Chapter 5). It is important to identify technique-related factors as modification of these factors may prevent injury, although ball release speed may be compromised due to this modification.

7.5 Longitudinal Follow Up

While it is important to consider which variables to investigate as part of the methodology, a careful consideration of the methodology in terms of follow up period is just as vital. Many of the factors measured in cricket are likely to change with time, due to normal variation, training factors, injury and a myriad of other variables, but almost all studies performed in the past are cross sectional. The need for longitudinal studies was therefore identified. Chapters 2, 4, 5 and 7 investigate the difference in variable status at the start and at the end of a cricket season. This longitudinal follow up gives these papers scientific value above cross sectional studies as meaningful cause-effect inferences can be made and change over time can be judged. At the same time the dropout rate in these papers were very low which makes inferences from the data more powerful.

7.6 The Power Phase

In a number of studies the pace bowling phase between back foot placement and front foot placement, namely the back foot placement phase was investigated. Shoulder, pelvis and foot positions during this phase was used to classify the bowler's action as front on, side on, semi-open and mixed. However this is not the phase where the highest kinetic forces act upon the body of the pace bowler and the bowler's back is in a relatively neutral position during the

back foot placement phase. For this reason Chapters 3, 4, 5 and 6 investigate different variables at the start (front foot placement) and end (ball release) of the front foot contact position or power phase. This is the phase where the highest kinetic forces act upon the body and where the bowler is subsequently at his most vulnerable to injury.

7.7 Performance in Pace Bowling

Not only injury prevention appeals to the pace bowler, but also the attainment of a state of optimal performance. The same high load nature of the pace bowling action that predisposes the pace bowler to injury also plays a role in faster ball release speeds. Therefore, the association between technique-related intrinsic factors namely, kinematic angles of the knee and spine, arm to thoracic angle as well as ball release height; and ball release speed are investigated in Chapter 5.

Furthermore, as it is shown in Chapters 4 and 5 that a more flexed knee is associated with injury prevention, while a more extended knee is associated with high ball release speeds, Chapter 6 aims to link knee proprioception to knee angle during front foot placement and subsequent ball release speeds. However, an association between knee joint proprioception in arbitrary and functional, sport-specific positions could not be established; nor could an association between knee angle during front foot placement and ball release position, or ball release speed be established. The further study of intrinsic factors that may be related to both injury prevention and improved performance has emerged in this thesis and should be encouraged in subsequent studies.

7.8 Physical Adaptation Unique to the Pace Bowler

Another intrinsic factor that is investigated in this thesis is abdominal muscle thickness and activity. The pace bowling action, due to its asymmetrical nature, leads to muscle imbalances which may predispose the pace bowler to injury, but which may also protect the pace bowler against injury. Awareness of the presence of physical adaptations unique to the pace bowler will inform the assessment and clinical reasoning processes of health and rehabilitation professionals. Chapter 7 investigated the side to side asymmetries in the abdominal musculature as found in this homogenous group of pace bowlers. Asymmetries such as these develop as a result of the high number of repetitions of the asymmetrical pace bowling action and are unavoidable in the pace bowler. Abdominal muscle thickness can be associated with both injury and performance, but further research in this area is advocated.

The focus of this thesis is thus on the association between intrinsic factors, injury and performance related to the cricket pace bowler as well as on muscle imbalances inherent in the pace bowler. The aims of the thesis are stated in the following section.

8. Aims of the Thesis

The overall aim of this thesis is to establish if there are associations between intrinsic factors, injury and performance as well as to establish whether muscle adaptation is present in cricket pace bowlers. The specific objectives for each of the papers are as follows:

Paper 1 (Chapter 2):

To establish any relationship between static and dynamic balance ability, lumbo-pelvic movement control and injury at the beginning and at the end of a cricket season.

To establish the relationship between the lumbo-pelvic movement control, balance ability and injury.

Paper 2 (Chapter 3):

To establish whether lumbar propioception (as measured by joint position sense) in the neutral lumbar spine position; as well as lumbar positions corresponding to those at front foot placement and ball release positions of the cricket pace bowling action are related to previous injury, injury sustained during the cricket season under review, specific low back injury as well as injury specifically sustained during the bowling action.

Paper 3 (Chapter 4):

To compare three dimensional spinal and knee kinematics at the start to that at the end of a cricket season.

To compare three dimensional spinal and knee kinematics between injured and non-injured pace bowlers.

Paper 4 (Chapter 5):

To establish if there is a relationship between three dimensional kinematics of the pace bowling action including spinal, knee, arm to thorax angles, ball release height and performance variables, namely speed and accuracy, at the start as well as at the end of a cricket season.

Paper 5 (Chapter 6):

To establish if knee joint position sense in pre-defined angles of 140˚ and 160˚ of knee extension as well as functional, reproduced, closed-chain knee positions at front foot placement and ball release, predict ball release speed.

Paper 6 (Chapter 7):

To determine the abdominal muscle thickness, to compare the side to side differences in thickness, as well as thickness measured at the start and again at the end of a cricket season of transverses abdominus (TA), obliquus abdominis internus (OI) and oblique abdominis externus (OE) muscles in a group of amateur pace bowlers.

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CHAPTER 2 – Paper 1: Olivier B, Stewart AV, Olorunju SAS and McKinon W (2013) Static and Dynamic Balance Ability, Lumbo-Pelvic Movement Control and Injury Incidence in Cricket Pace Bowlers, *Journal of Science and Medicine in Sport* (in press)

At the time of this thesis submission, paper 1 was in press at the *Journal of Science and Medicine in Sport,* as an original article. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article and general formatting is aligned with the requirements of the specific journal.

1. Original Paper

Title: Static and Dynamic Balance Ability, Lumbo-Pelvic Movement Control and Injury Incidence in Cricket Pace Bowlers

Authors: Benita Olivier, Aimee Stewart, Steve Olorunju, Warrick McKinon

Abstract
Objective: This study aimed to establish the difference in lumbo-pelvic movement control, static and dynamic balance at the start and at the end of a cricket season in pace bowlers who sustained an injury during the season and those who did not.
Design: This is a longitudinal, observational study.
Method: Thirty two, healthy, injury free, male premier league fast, fast-medium and medium pace bowlers between the ages of 18 and 26 years (mean age 21.8years, SD 1.8years) participated in the study. The main outcome measures were injury incidence, lumbo-pelvic movement control, static and dynamic balance ability.
Results: Fifty three percent of the bowlers (n=17) sustained injuries during the reviewed cricket season. Lumbo-pelvic movement control tests could not discriminate between bowlers who sustained an injury during the cricket season and bowlers who did not. However, performance in the SLBT ($p=0.03$; CI 4.74 -29.24) and the SEBT ($p=0.02$; CI 1.28 - 11.93) as measured at the start of the season, was better in bowlers who did not sustain an injury during the season.
Conclusion: The improvement in the lumbo-pelvic movement control and balance tests, suggests that the intensity and type of physical conditioning that happens throughout the season may have been responsible for this improvement. Poor performance in the SLBT and the SEBT at the start of the cricket season may be an indication that a bowler are at heightened risk of injury.

Key words: lumbo-pelvic movement control; balance; injury; cricket, fast bowler, pace bowler

1. Introduction

In the game of cricket, players take on specific roles which include batting, wicket keeping, fielding, spin bowling and pace bowling. Each of these roles has its own demands and its own unique set of associated injuries. The cricket pace bowling action is a dynamic, complex sequence of high speed movements that may be repeated between 300 and 600 times each week during a cricket season.[1] During the pace bowling action, substantial forces are placed on the lumbar spine facilitating faster ball release speeds, but at the same time predisposing the bowler to injury.[2] Combined postures of lumbar extension, contralateral side-flexion and ipsilateral rotation during the delivery stride are involved in the pathomechanics of low back injuries.[2,3,4] Such movements, in combination with other biomechanical aspects of pace bowling, such as increased shoulder counter rotation during the delivery stride,[2] are part of the bowling technique and with insufficient muscular stability and control of movement could lead to injuries including, lumbar soft tissue injuries and stress fractures.[3]

Bowling related injuries have been documented as being the result of the normal strain of the bowling technique, but individual muscle dysfunction might contribute to injury. One example of the effect of muscle dysfunction is the inability of individual muscles to control excessive motion at a specific joint. This may result in local hypermobility, tissue pathology and pain.[5,6] Comerford and Mottram[5,7] have developed a theoretical model which states that functional stability is dependent on integrated local and global muscle function. Poor control of movement is described by Comerford and Mottram[7] as the lack of ability to actively control or prevent a compensatory movement when required or instructed to do so. Specific to cricket pace bowlers, overloading the spine with high load forces during bowling in the presence of uncontrolled movement and muscle imbalance further predispose bowlers to injury.[8] Although extensive research is still needed to develop this theoretical model into evidence, it may serve as an explanation of how movement dysfunction can predispose the pace bowler to injury.

Balance is defined as the ability to keep the body's centre of mass within the limits of the base of support.[9] Neuromuscular control and especially superior balance ability is likely to be important during the bowling action due to its high load, dynamic and asymmetrical nature. The importance of optimal balance ability in the bowling action is emphasised by the known relationship between poor balance and a higher incidence of injury, as well as the relationship between highly developed balance ability and the reduced incidence of injuries as was established in other populations.[10,11]

Therefore the aim of this study was to investigate the relationship between static and dynamic balance ability, lumbo-pelvic movement control and injury in cricket pace bowlers at the start and end of the cricket season. This may assist in the development of injury prevention programmes.

2. Materials and Methods

Ethical approval was obtained from the Human Research Ethics Committee of the associated tertiary institution. Access to the database of premier league pace bowlers was obtained from the Gauteng Cricket Board. Male, premier league fast, fast-medium and medium pace bowlers were randomly invited to participate in this study. Bowlers were screened for inclusion when they were first contacted telephonically. Bowlers had to be healthy and injury free at the start of the cricket season. Bowlers suffering from any clinical apparent injuries or injuries preventing them from participating in bowling and bowlers who have undergone previous surgery to the spine or limbs were excluded from this study. Written informed consent was granted by all participants Bowlers completed a self-administered questionnaire enquiring about the length of time they had been a bowler, their bowling position in the

bowling order and injuries sustained previously. Content and construct validity was found to be acceptable for this self-developed questionnaire. Each bowler underwent a pre-season testing regimen administered by the first author who was blinded to the injury history of the bowler. The occurrence of injuries was recorded monthly during the cricket season via the completion of self-administered questionnaires. For the purposes of this study an injury was defined as a musculoskeletal condition that resulted in the loss of at least one day of sporting activity or that occurred during a sporting activity that required medical attention and which forced the bowler to quit the activity.[6,12] At the end of the cricket season all bowlers again underwent the same testing regimen as was administered pre-season.

Bowlers underwent single leg balance- (SLBT), star excursion balance- (SEBT) and lumbo-pelvic movement control tests (Table 1). The SLBT were conducted with the bowler's eyes closed standing on a stable surface, eyes open standing on an unstable surface (Airex® balance pad; Fitter International Inc., Calgary), and eyes closed on an unstable surface. The time was recorded when the bowler lost his balance, opened his eyes or when 180 seconds was reached.[10]

The SEBT was conducted by instructing the bowler to stand on his right leg and reach as far as possible with his left leg in an anterior, postero-lateral and postero-medial direction.[13,14] The bowler had to lightly touch a spot as far as possible in a specific reach direction without transferring his weight onto his reach leg. The bowler then had to return to double leg stance without changing the base of support of the stance leg. The test was abandoned when the bowler removed his hands from his hips, failed to maintain unilateral stance, lifted or moved the stance foot, touched down with the reaching limb, or fail to return to the starting position. The test was repeated with the bowler standing on the other leg.[14]

Leg length was measured from the most distal end of the anterior superior iliac spine (ASIS) to the most distal point of the lateral malleolus. All reach values were then calculated as a percentage of leg length (reach distance in cm/leg length in cm *100). Combined reach scores were calculated by dividing the sum of the reach distance in the anterior, postero-lateral and postero-medial directions by three times the limb length, then multiplied by 100.[15] The different movement control tests used in this study are itemised and detailed in Table 1.[6,16,17]

The SLBT and SEBT indicated excellent inter- and intra-rater reliability. Only intra-rater reliability was established for all the movement control tests as the same researcher performed these tests. Tests were recorded and video clips were rated one week later to establish intra-rater reliability. The ICC was used for all continuous variables. The weighted kappa coefficients were calculated for the rest of the variables which were all binary. Agreement above 0.75 was described as excellent and below 0.75 as poor.[18] The prone lying active knee flexion (PLKF) to 90˚ on the right (k=0.71), PLKF to 120˚ on the left (k=0.59) and the one leg standing (OLS) on the left (ICC=0.72) and right (ICC=0.50) showed poor agreement and was as a result not included in the presentation and discussion of results.[16,19] All other movement control tests showed excellent agreement.

Data were analysed using STATA Data Analysis and Statistical Software (version 11.2; Texas: USA). Bowlers were divided into two groups: bowlers who sustained a lower quarter (LQ) (low back and lower limb) injury during the cricket season under review are referred to as "LQ injury" and those who did not sustain an injury are referred to as "no LQ injury." All data were assessed for normality before testing and $p<0.05$ defined statistical significance. Binary data were organised into contingency tables using the Fisher's exact test. Associations were established for continuous data using the independent Student t-test and the Mann-Whitney U test (LQ injury vs no LQ injury) as well as the paired Student t-test and the Wilcoxon matched pairs test (pre-season vs post-season).

Table 1

Lumbo-pelvic movement control tests used in this study with body positions depicted and described.[5,6,16,17]

Position: Standing	
Waiter's bow (WB) 	Position bowler's spine in neutral position - midrange between anterior and posterior pelvic tilt. Instruct bowler to keep spine in neutral while bending forwards (flexion) at the hips to ± 50º without movement (flexion/extension) of the low back. Correct: forward bending at the hips without movement of the low back (50º-70º flexion hips). Incorrect: angle hip flexion without low back movement less than 50º or flexion occurring in the low back.
Dorsal tilt of the pelvis (DTP) 	Dorsal pelvic tilt actively done in upright standing. Correct: actively in upright standing (gluteus activity), keeping thoracic spine in neutral, lumbar spine moves towards flexion/no gluteus activity, compensatory flexion in the thoracic spine. Incorrect: pelvis does not tilt or low back moves towards extension or compensatory flexion in the thoracic spine.
One leg standing (OLS) 	From normal standing to one leg stance: measurement of lateral movement of the umbilicus (position: feet one third of trachanter distance apart). Stand on right leg. Correct: the distance of the transfer is symmetrical right and left. Incorrect: Lateral transfer of the umbilicus more than 10cm or the difference between sides more than 2cm. Repeat on left leg.
Position: 4 point kneeling	
Rocking forwards (RF) 	Bowler in four point kneeling/quadruped position. Correct: Rocking forwards (60º hip flexion) without extension movement of the low back. Incorrect: Hip movements leads to extension of the low back.

Rocking backwards (RB) 	Transfer of the pelvis backwards ("rocking") in a quadruped position keeping low back in neutral. Correct: 120º hip flexion without (flexion) movement of the low back by transferring the pelvis backwards. Incincorrect: hip flexion causes flexion in the lumbar spine.
Position: Sitting	
Sitting knee extension (SKE) 	Upright sitting with corrected lumbar lordosis: extension of the knee without movement (flexion) of the low back. Correct: upright sitting with corrected lumbar lordosis: extension of the knee without movement of the low back (30º-50º extension normal). Incorrect: low back moving in flexion. Bowler is not aware of the movement in the low back.
Position: Crooklying	
Knee lift abdominal test (KLAT) 	Crook lying. Position pressure biofeedback horizontally under lumbar spine with the lower edge at the level of the PSIS and inflate to pressure of 40mmHg. Bowler performs 2 inspirations and 2 expirations. Readjust pressure to 40mmHg. Bowler should maintain neutral spine. Bowler lifts right foot off the plinth to 90º of hip flexion with knee flexion. Record pressure change. Repeat on the left.
Bent knee fall out (BKFO) 	Partial crook lying (one leg bent one leg straight). Pressure biofeedback positioned vertically under lumbar spine on the side of bent leg 2cm caudal to PSIS and inflated to pressure of 40mmHg. Bowler performs 2 inspirations and 2 expirations. Readjust pressure to 40mmHg. Bowler should maintain neutral spine. A folded towel is put under the side of the extended leg to keep pelvis at the same height. Bowler lowers bent leg to approx 45º of abduction/lateral rotation. Record pressure changes on outward movement. Repeat with both legs. Without biofeedback - both legs bent in crook lying. Correct: active abduction of one hip without rotational movement of the pelvis and low back. Incorrect: umbilicus moves sidewards, pelvis rotates or tilts. Repeat on the other side.
Position: Prone	
Prone lying active knee flexion (PLAKF) 	Correct: active right knee flexion at least 90º without extension movement of the low back and pelvis. Incorrect: During knee flexion, the low back does not stay neutral maintained but moves into extension or rotation. Repeat on the left.

3. Results

Thirty two, male, premier league fast, fast-medium and medium pace bowlers, aged 18 to 26 years (mean age 21.8years, SD 1.8years), participated in this study. Most participants were classified as medium pace (n=16; 50%), opening bowlers (n=25; 78%). Seven bowlers (22%)

were first change bowlers, 11 (34%) were fast bowlers and 5 (16%) were fast-medium bowlers.

The prevalence and incidence of injuries amongst bowlers are shown in Table 2. Eighty eight percent (n=28) of bowlers had sustained previous cricket related injuries. Fourteen percent (n=4) of these bowlers injured their lower back. During the season 53% (n=17) sustained injuries. A high number of injuries were sustained during bowling (n=16; 94%).

There was no statistically significant difference between the group of bowlers who did and the group who did not sustain an injury during the cricket season in terms of the following variables: age, type of bowler, handedness, bowling experience and previous injuries sustained (p=0.06 - 0.68).

Bowlers performed better in the SLBT at the start of the season than at the end of the season (standing on left leg in injured bowlers p=0.02, CI 4.74 -29.24; standing on right leg in non-injured bowlers p=0.02, CI 15.95 - 43.02). At the start of the season, injured bowlers were able to stand for a shorter period of time on an Airex balance pad with their eyes closed when compared to non-injured bowlers (p=0.03, CI 1.13 - 2.31). The LQ injury group performed worse in the SEBT posterior medial reach direction while standing on the right leg than the no LQ injury group (p=0.02, CI 9.44 - 11.81). The bowlers that sustained an injury during the season performed worse in the BKFO on the left at the start of the season than at the end of the season (p=0.01, CI 1.05 - 5.20). Both groups of bowlers performed worse in the KLAT at the start of the season compared to at the end of the season (p=0.02, CI 1.83 - 8.17).

Table 2.

The prevalence, incidence and nature of injuries amongst participants (n=32).

	Number of bowlers (n)	**Number (percentage)**
Injuries sustained previously	**32**	
Yes		**28 (88%)**
No		**4 (12%)**
Number of injured anatomical areas	28	
One		9 (32%)
Two		11 (39%)
> Three		8 (29%)
Injury sustained during bowling	28	
Yes		18 (64%)
No		10 (36%)
Low back injury	28	
Yes		4 (14%)
No		24 (86%)
Injuries sustained during the cricket season	**32**	
Yes		**17 (53%)**
No		**15 (47%)**
Number of injured anatomical areas	17	
One		7 (41%)
Two		5 (29%)
> Three		5 (29%)
Injury sustained during bowling	17	
Yes		16 (94%)
No		1 (6%)
Low back injury	17	
Yes		4 (24%)
No		13 (76%)

No difference was found in the number of positive nominal lumbo-pelvic movement control tests shown in Table 1 [waiter's bow (WB), dorsal tilt of the pelvis (DTP), rocking forwards (RF), rocking backwards (RB), sitting knee extension on the left (SKE L), sitting knee extension on the right (SKE R), bent knee fall out on the left (BKFO L) and bent knee fall out on the right (BKFO R)] between the two groups ($p=0.12 – 0.58$). Furthermore, when analysed independently, no difference was found between the two groups in the ability to perform each test ($p=0.07 – 0.45$).

Table 3.
Lumbo-pelvic movement control-, static and dynamic balance tests in bowlers who sustained an injury and those who did not sustain an injury during the cricket season.

	Pre-season				Post-season				LQ inj (pre vs Post)		No LQ inj (pre vs post)	
	LQ inj m (SD) n=17)	**No LQ inj m (SD) (n=15)**	**p**	**95% CI**	**LQ inj m (SD) (n=16)**	**No LQ inj m (SD) (n=14)**	**p**	**95% CI**	**p**	**95% CI**	**p**	**95% CI**
SLBT: Eyes closed on stable surface – left leg (s)	11.60 (14.34)	23.10 (20.92)	0.15	-24.31 - 1.33	15.67 (18.84)	14.00 (11.40)	0.77	-22.03 - 7.18	0.39	-11.91 - 3.94	0.64	-6.05 - 21.75
SLBT: Eyes closed on stable surface – right leg (s)	13.37 (13.49)	21.10 (20.76)	0.10	-20.19 - 4.79	12.63 (11.48)	14.42 (14.60)	0.71	-11.55 - 7.97	0.10	-8.83 - 10.45	0.33	-2.32 - 17.15
SLBT: Eyes open on Airex balance pad – left leg (s)	31.05 (23.16)	27.74 (17.79)	0.33	-11.76 - 18.38	15.12 (14.36)	23.66 (14.61)	0.12	-19.39 - 2.31	0.02 *	4.74 - 29.24	0.33	-4.52 - 15.18
SLBT: Eyes open on Airex balance pad – right leg (s)	28.99 (22.86)	31.55 (23.11)	0.96	-19.18 - 14.07	20.98 (16.31)	25.03 (21.13)	0.56	-18.07 - 9.97	0.07	-1.34 - 20.56	0.02 *	15.95 - 43.02
SLBT: Eyes closed on Airex balance pad – left leg (s)	3.50 (2.27)	3.76 (1.95)	0.58	-1.80 - 1.28	3.29 (1.83)	3.50 (1.77)	0.75	-1.56 - 1.14	0.68	-1.19 - 1.88	0.78	-1.12 - 1.74
SLBT: Eyes closed on Airex balance pad –	3.47 (1.683)	4.06 (2.98)	0.03 *	-2.31 - -1.13	3.00 (1.53)	3.38 (1.385)	0.48	-1.48 - 0.72	0.35	-0.69 - 1.78	0.80	-1.23 - 2.71

right leg (s)												
SEBT: Anterior reach standing on left leg**	66.39 (7.48)	66.49 (8.37)	0.66	-5.82 - 5.62	68.52 (8.29)	65.08 (9.69)	0.30	-3.28 - 10.16	0.20	-7.21 - 1.63	0.86	-4.62 - 5.16
SEBT: Postero-medial reach standing on left leg**	91.46 (9.41)	95.20 (14.62)	0.09	-12.52 - 5.02	93.64 (14.15)	92.94 (13.13)	0.89	-9.56 - 10.96	0.46	-8.99 - 3.05	0.64	-3.83 - 7.12
SEBT: Postero-lateral reach standing on left leg **	81.11 (13.64)	88.10 (14.93)	0.72	-17.30 - 3.32	89.21 (13.94)	87.45 (15.30)	0.74	-9.17 - 12.70	0.03 *	-11.93 -- 1.28	0.97	-5.72 - 8.03
SEBT: Anterior reach standing on right leg **	67.49 (8.15)	68.73 (10.20)	0.39	-7.87 - 5.39	72.19 (7.46)	65.53 (10.19)	0.05	0.04 - 13.28	0.04 *	-9.81 - - 0.50	0.55	-3.06 - 6.98
SEBT: Postero-medial reach standing on right leg**	90.07 (10.18)	91.26 (18.54)	0.02 *	-11.81 - -9.44	96.28 (11.29)	97.19 (14.24)	0.85	-10.46 - 8.65	0.03 *	-11.94 - - 0.69	0.03 *	-13.99 - -0.75
SEBT: Postero-lateral reach standing on right leg**	78.54 (13.27)	84.76 (14.32)	0.76	-16.18 - 3.74	86.18 (14.58)	84.78 (17.73)	0.81	-10.68 - 13.49	0.01 *	-12.41 - - 0.79	0.86	-6.56 - 7.06
SEBT: Combined reach standing on left leg**	79.65 (7.98)	83.26 (11.48)	0.16	-10.68 - 3.45	83.79 (10.47)	81.82 (11.18)	0.62	-6.13 - 10.07	0.06	-8.40 - 0.16	0.81	-3.96 - 6.01
SEBT: Combined reach standing on right leg**	78.70 (9.05)	81.59 (12.83)	0.18	-10.82 - 5.060	84.88 (9.62)	82.50 (12.70)	0.56	-5.98 - 10.75	0.01 *	-9.69 - - 2.02	0.07	-5.72 - 2.28
BKFO on the left (mmHg)	8.12 (2.32)	6.13 (3.58)	0.10	-0.17 - 4.14	5.00 (3.71)	4.71 (2.95)	0.82	-2.24 - 2.81	0.01 *	1.05 - 5.20	0.17	-0.86 - 4.29

BKFO on the right (mmHg)	6.06 (4.13)	5.60 (2.53)	0.07	-2.06 - 2.97	5.69 (3.26)	6.36 (3.10)	0.57	-3.06 - 1.72	0.81	-2.07 - 3.07	0.35	-2.41 - 1.12
KLAT on the left (mmHg)	10.71 (5.82)	8.27 (7.59)	0.31	-2.41 - 7.29	9.75 (5.46)	7.86 (5.68)	0.36	-2.28 - 6.06	0.57	-2.16 - 4.41	0.95	-4.74 - 7.03
KLAT on the right (mmHg)	13.88 (6.95)	15.53 (11.14)	0.07	-8.27 - 4.97	8.88 (4.95)	7.79 (7.32)	0.63	-3.53 - 5.71	0.01 *	1.83 - 8.17	0.02 *	1.03 - 14.68

LQ – low quarter (low back and/or lower limb injury); SLBT – single leg balance test; SEBT – star excursion balance test; BKFO – bent knee fall out test; KLAT – knee lift abdominal test; inj – injury; s – seconds; mmHg – millimetres of Mercury; m – mean; SD – standard deviation; CI – confidence interval

* Statistical significance ($p<0.05$); ** Normalized reach distances (reach distance in cm/leg length in cm*100)

4. Discussion

The results pertaining to static and dynamic balance ability, lumbo-pelvic movement control and injury as found at the start and at the end of the cricket season in pace bowlers are included in the discussion below. Performance in the lumbo-pelvic movement control, static and dynamic balance tests was better at the end of the cricket season. Performance on the SLBT and SEBT was better in bowlers who did not sustain an injury during the season, while the lumbo-pelvic movement control tests did not discriminate between bowlers who sustained an injury and those who did not.

In this study, a large proportion of bowlers sustained injuries during the reviewed cricket season (Table 2). In a South African study on international cricket players over two cricket seasons it was found that bowling accounted for the highest percentage (27%) of injury.[20] A high number of injuries were sustained during the bowling action (94%) in this study. Pace bowlers are more prone to injury than spin bowlers due to the fact that their run up is longer and the ball is delivered with more momentum.[21] The percentage of low back injuries (24%) found in this study is similar to what was found by Stretch[12] and Orchard et al.[21] Between 24% and 32.6% of bowlers sustained injuries to the trunk, lower back and lower limbs in their studies.[12,21] The most frequent injury sustained by the pace bowler is lumbar soft tissue injuries and lumbar stress fractures,[12,21] which in part is due to contralateral lumbar side flexion that takes place during the bowling action.[22] These high injury rates indicate that the pace bowler is particularly prone to injury.

Especially, the bowlers in the LQ injury group improved in the elements needed to perform the SEBT (Table 3). These elements are incorporated when the centre of gravity is moved outside the base of support and consequently physical capabilities including strength,[23] control, flexibility, joint range of movement, coordination and muscle recruitment patterns[24] are required. These physical capabilities are likely to be part of the training programme that takes place during the cricket season and responsible for improvement in dynamic balance. Jakobsen et al.[25] explains the improvement in balance in that neural adaptation in the somatosensory, visual and vestibular system takes place in accordance to the specific needs of the sport. The improved neural adaptation may be as a result of enhanced fusimotor firing rate, increased motor neuron excitability and increased levels of descending neural pathways as well as decreased neural inhibition.[26] As a result of these known benefits of training, it is likely that training induced improvements in core and lower limb strength, aerobic capacity, as well as other elements unique to the requirements of the bowling action, dynamic balance were improved in both groups of bowlers. The SEBT (postero-medial direction) on the right leg when performed at the start of a cricket season can identify bowlers who are predisposed to sustain a low back and/or lower limb injury. Poor SEBT reach distances at the start of season may predict injury,[24] while improvement at the end of the season may indicate the effect of rehabilitation or intense training during the cricket season.

The normalised postero-medial and postero-lateral reach distances found in the current study is similar to the reach distances found by Hertel et al.[13] and slightly higher than what was found by Robinson and Gribble.[14] However reach distances are lower than what was found by Plisky et al.[24] Plisky et al.'s[24] study population included high school basketball players, while the current study as well as those of Hertel et al.[13] and Robinson and Gribble[14] studied young adults with a mean age between 20.9 and 23.2 years. Additionally, the normalised anterior reach distances in the current study are lower than the above mentioned studies. The difference in results may stem from the different study populations as Hertel et al.[13] did not specify sports activity involvement and the majority of Robinson and Gribble's[14] study population was not involved in sports either. Pace bowlers may thus display a unique adaptation of dynamic balance although further research is advised.

Furthermore, bowlers who sustained an injury during the season were not able to balance on the Airex balance pad with their eyes closed for as long as the bowlers who did not sustain an injury (Table 3). The SLBT when performed on an unstable surface, with the eyes closed, at the start of a cricket season can identify bowlers who are predisposed to sustain a lower quarter injury. Maintaining balance during sport specific activities depends on three main sensory components, namely, proprioception, vision and vestibular function.[24,27] The proprioceptive system was optimally challenged when vision was removed and the surface was unstable which caused bowlers in the injured group to perform poorly. Poor proprioception in this case may predict injury. Optimal balance is crucial in the sports arena where bowlers rely on balance especially during the single limb support phase of the bowling action where the bowler has to maintain his balance during this high load activity. Although bowlers performed better in the SLBT on the Airex balance pad with eyes open at the start compared to at the end of the season, due to the poor test-retest reliability (k=0.21) the SLBT cannot be used as a reliable clinical measure of improvement in balance.[28] It is however interesting to note that poor performance amongst injured bowlers in both the SLBT and the SEBT were identified while standing on the right leg, especially as 16 of the 17 injured bowlers were right hand bowlers. This may indicate the adaptation of the neuromuscular control system as a result of the asymmetrical bowling action where the left leg takes most of the ground reaction forces which is the highest during the front foot placement phase.

The improvement in performance of the BKFO and the KLAT indicates that less lumbo-pelvic movement also occurred when these tests were performed at the end of the season (Table 3). The KLAT and BKFO gives an indication of the ability to stabilise the lumbopelvic area proximally while the legs move distally.[5] Improvement in performance of the movement control tests may indicate greater lumbo-pelvic stability and a decrease in uncontrolled movement. Proprioception and co-ordinated muscle action require sensory, biomechanical and motor-processing strategies. Learned responses from previous experience play a role in improvement of these components and are influenced by conditioning.[5] The findings of the current study suggest that greater proprioception and muscle control may reduce risk of lower quadrant injury. This may be due to reduction in uncontrolled movement and subsequent reduction in adverse loading within joints. Both the injured and non-injured groups performed better in the KLAT which may indicate the ability of this test to measure change, but it also may indicate the poor discriminative ability of the KLAT. Roussel et al.[6] found that the KLAT and WB accurately predicted injury in 78% of dancers however, they did not find any relationship between the BKFO and lower quarter injury. This difference in findings may be related to the difference in sport specific needs in dancers and pace bowlers. In this study, no difference was found between injured and non-injured bowlers in their performance of the BKFO, KLAT (Table 3) or any of the other lumbo-pelvic movement control tests. Luomajoki et al.[17] established that patients with low back pain had more positive movement control tests than healthy controls. Their battery of tests included six movement control tests, while in this study eight movement control tests were analysed. Furthermore, Luomajoki et al.'s[17] participants suffered from low back pain specifically, while the bowlers in this study suffered from low back and/or lower limb injury. This may explain why no difference was found in the number of positive tests in the two groups of bowlers. Although lumbo-pelvic movement control tests can measure change, further research is needed to establish the discriminative validity of these tests in cricket pace bowlers.

The results found in this study are strengthened by the fact that both the LQ injury and the no LQ injury groups were similar in terms of potential confounding factors including age, type of bowler and previous injuries sustained. Dynamic balance tests were done at the start as well as at the end of the cricket season in the morning, but it may not have taken place at

exactly the same time of the day.[23] Gribble et al.[23] suggest that dynamic balance may be better in the morning, than in the afternoon or evening.
Although the sample size was sufficient for the analysis performed in this study, the sample size was too small for associations between group characteristics (type of bowler, bowling experience, handedness) and injury. Height and weight were not recorded as part of this study. However, leg length was measured and was in line with the average leg length that was found in other studies. It was furthermore believed that the fact that all bowlers were playing in the same cricket league and on the same competitive level contributed to the homogeneity of the group.
Future research comprising of an in-depth analysis of training programmes followed by amateur bowlers, may indicate the specific components that influence movement control and balance ability in cricket pace bowlers.

5. Conclusion

The improvement in the lumbo-pelvic movement control, static and dynamic balance tests, suggests that the intensity and type of physical conditioning that happens throughout the season may have been responsible for this improvement. In this study, lumbo-pelvic movement control tests did not discriminate between bowlers who sustained an injury during the cricket season and bowlers who did not. However, performance in the SLBT and the SEBT was better in bowlers who did not sustain an injury during the season.

Practical Implications

- The single leg balance test when performed on an unstable surface, with the eyes closed, at the start of a cricket season can identify bowlers who are predisposed to sustain a low back and/or lower limb injury.
- The star excursion balance test especially while standing on the right leg when performed at the start of a cricket season can identify bowlers who are predisposed to sustain a low back and/or lower limb injury.
- The intensity and type of general, physical conditioning that happens throughout a cricket season may result in improvement in the star excursion balance test, bent knee fall out test and knee lift abdominal test when measured again at the end of a cricket season.

Conflict of Interest

None

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CHAPTER 3 – Paper 2: Olivier B, Stewart AV and McKinon W (2013) Injury and Lumbar Reposition Sense in Cricket Pace Bowlers in Neutral and Pace Bowling Specific Body Positions, *The Spine Journal* (in press)

At the time of this thesis submission, paper 2 was accepted for publication in *The Spine Journal,* as an original article. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article and general formatting is aligned with the requirements of the specific journal.

1. Original Paper

Title: Injury and Lumbar Reposition Sense in Cricket Pace Bowlers in Neutral and Pace Bowling Specific Body Positions

Authors: Benita Olivier, Aimee Stewart, Warrick McKinon

Abstract

BACKGROUND AND CONTEXT: The cricket pace bowling action consists of a complex sequence of forceful actions, involving practiced, particular movements of the lumbar spine. The nature and repetition of the pace bowling action is known to be associated with a high incidence of low back injuries.

PURPOSE: This study aimed to establish whether lumbar propioception (as measured by joint position sense) in the neutral lumbar spine position; as well as lumbar positions corresponding to those at front foot placement and ball release positions of the cricket pace bowling action were related to previous injury and injury sustained during the cricket season under review. Injuries specifically sustained during the bowling action and those specific to the low back were explicitly investigated.

STUDY SETTING: Longitudinal study with participants tested at the start and monitored over the duration of a cricket season.

PARTICIPANT SAMPLE: Seventeen male cricket pace bowlers between the ages of 18 and 26 years participated in this study.

OUTCOME MEASURES: Physiological outcome measures were used. Lumbar position sense was established using electrogoniometry.

METHODS: Lumbar reposition error was measured in three positions (neutral lumbar spine, front foot placement and ball release bowling positions). In each position lumbar orientation was determined in the sagittal (flexion-extension) and frontal (left-right lateral flexion) planes. Wilcoxon Matched-Pairs Ranks and Kruskal-Wallis tests were used to establish the relationship between variables. Funding was granted by the Carnegie Foundation, the National Research Foundation and the South African Society of Physiotherapy.

RESULTS: Reposition error, as a measure of proprioception, was associated with general injuries sustained in the past and during the cricket season under review, low back injuries, as well as injuries sustained during the bowling action ($p<0.05$).

CONCLUSION: Low back injury prevention methods are particularly needed due to the high load nature of the pace bowling action. If the proprioception of the lumbar spine is improved in pace bowlers, their risk of lumbar injury can potentially be reduced.

Key words: Lumbar, reposition error, position sense, proprioception, cricket pace bowlers, injury

Introduction

In cricket, the role of the pace bowler is to bowl an accurate delivery as fast as possible to the opposing batsman. Of the roles a cricketer may play, bowling accounts for the highest percentage of injuries (29%) when compared to fielding and wicket keeping (27%), and batting (19%) [1]. Forty percent of injuries sustained by the pace bowler are classified as lumbar spine injuries [2]. The primary mechanism of injury is thought to be associated with the delivery and follow through of the pace bowler [3]. In particular, preferential asymmetrical hypertrophy of the quadratus lumborum muscle [4], shoulder depression and horizontal flexion strength in the preferred limb, quadriceps strength of the non-preferred limb, increased trunk rotation between back foot and front foot placement phases and a greater ball release height [5] have been found to predispose the pace bowler to low back injury.

The cricket pace bowling action relies on a complex sequence of movements needed for optimum performance as well as injury prevention. Proprioception is crucial for the control of this complex sequence of movements. Proprioception is defined as the complex interaction between afferent and efferent receptors that control sensation of position and movement input derived from muscle, joint and skin receptors [6; 7]. Joint position sense is a form of proprioception and is described as the ability to perceive the orientation of a body segment in space [7]. Position sense is mainly sensed by muscle spindles, while skin and joint receptors play a supporting role [8].

Lumbar proprioception deficit has been described by Parkhurst [9] using repositioning sense and other methods. In the latter study it was surmised that injury to muscle spindles, impairs proprioception which in turn result in errors in the positioning of the low back, thereby influencing the ability of a person to perform tasks. The link between decreased proprioception and peripheral joint injury has been established [10; 11]. In this way, proprioception may predispose the pace bowler to injury due to impaired neuromuscular protective reflexes and coordination. Moreover, Forwell and Carnahan [11] found that poor proprioception may be a risk factor for injury even after muscle and ligament integrity have been restored.

The study of lumbar proprioception is particularly important in cricket pace bowlers, a group vulnerable to low back injuries. This study aimed to establish whether lumbar propioception (as measured by joint position sense) in the neutral lumbar spine position; as well lumbar positions corresponding to those at front foot placement and ball release positions of the cricket pace bowling action were related to previous injury, injury sustained during the cricket season under review, specific low back injury as well as injury specifically sustained during the bowling action.

Methods

Participants

Amateur cricket pace bowlers playing premier league club cricket were invited to participate in this study. A list of pace bowlers' contact details was obtained from the cricket governing body. After a process of randomisation, bowlers were invited telephonically. Bowlers suffering from any clinical apparent injuries or injuries preventing them from participating in bowling and bowlers who have undergone previous surgery to the spine or limbs were excluded from this study. All bowlers had four or more years of pace bowling experience at the time of testing. Ethical clearance was obtained from the associated tertiary institution's human research ethics committee.

Monitoring of injuries

Information regarding the status, nature and prevalence of any injuries sustained was collected at the start, monthly throughout the season and at the end of a cricket season using self-report measures via questionnaires. An injury was defined as: "a musculoskeletal condition that resulted in loss of at least one day of sporting activity or that occurred during a sporting activity that required medical attention and which forced the bowler to quit the activity". These questionnaires included information on general injuries sustained in the past, low back specific injury, injuries sustained during the cricket season and injuries sustained during the pace bowling action.

Procedures

Lumbar reposition sense was tested at the start of the cricket season. Spatial calibration of a telemetric electrogoniometer (Zebris®, Germany, Europe) was performed before each participant was tested. Bowlers were given time to warm up before the actual testing procedure started. The electrogoniometer was attached to the lumbar spine with adhesive strapping. The Bluetooth telemetric measuring system was fitted around the waist of the bowler in a position that did not hinder movement during the bowling action. The bowler was required to bowl one "match pace delivery" aimed at a right hand batsman. A high speed digital camera (PixeLINK® PL-A741, Ottawa, Ontario), synchronised to the electrogoniometer telemetry, captured the side on view of the pace bowler during the delivery stride. After the bowling action was completed, electrogoniometric angular data was collected using MyoResearch® (Scottsdale, Arizona) software at front foot placement and ball release positions as captured by the high speed camera. Lumbar position sense testing was done in standing body positions (bowlers eyes closed). The bowler's low back was positioned for five seconds into the same lumbar position that occurred at front foot placement, followed by five seconds of rest [12]. Thereafter he was instructed to reposition himself into the same position and to hold the position for three seconds [13]. The reposition error was calculated by subtracting the electrogoniometer reading of the initial position from that of the repositioned position. The same process was followed to position the bowler in the ball release position of bowling. Each bowler's low back was thus positioned into the exact front foot placement and ball release position that the bowler was in during those two phases of the bowling action. The latter body positions were defined in the following way (reference is made to a right arm bowler): Front foot placement was the first frame when the left toe marker reached its lowest position and ball release the first frame observed where the ball was no longer in contact with the bowler's hand [14].

Neutral lumbar spine body positions were assessed and were defined as the position midway between end-range lumbar flexion and end-range lumbar extension (Figure 1) [12]. The same procedure described to obtain reposition error in the front foot placement and ball release positions was followed (Figure 2).

Equipment

The electrogoniometer used in this study has previously shown to be reliable (ICC=0.92, p=<0.0001, CI 0.89-0.95) and accurate as compared to a benchmark standard plurimeter ($r > 0.99$, $P < 0.0001$) [15]. Placement of the electrogoniometer as used in this study is shown in Figure 1.

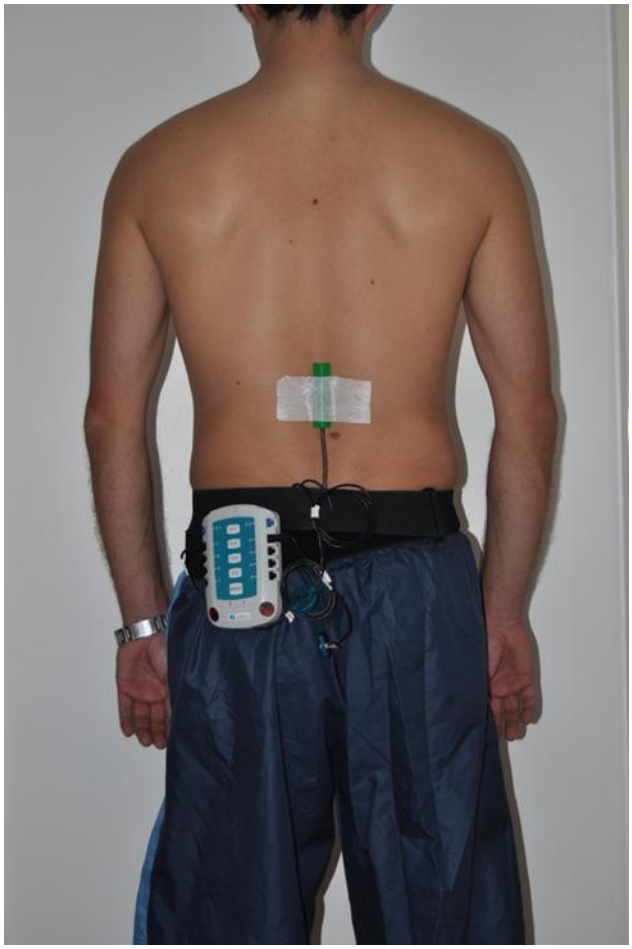

Fig 1. A cricket pace bowler in neutral lumbar spine position with electrogoniometer attached.

A)  B) 

Fig 2. A) Front foot placement position; B) Ball release position; of the pace bowling action.

Data analysis

Repositioning error was calculated as the difference between actual and participant-replicated target positions. Data were analysed using STATA Data Analysis and Statistical Software (version 11.2; Texas: USA). All data were assessed for normality with the Kolmogorov-Smirnov goodness-of-fit test. Statistical significance was defined as $p<0.05$. The Wilcoxon Matched-Pairs Rank and the Kruskal-Wallis tests were used to establish whether differences between groups exist.

Results

Seventeen bowlers between the ages of 18 and 26 years participated in the study. All bowlers were injury free at the time of testing. Seventy six percent (n=13) of bowlers had previously sustained general injuries and 23% (n=3) had previously sustained low back specific injuries. Forty seven percent (n=8) sustained injuries during the season under review and all of these injuries were sustained during the bowling action. All previous injuries were managed through the use of conservative modalities (medication, physiotherapy, rest) and none of the bowlers underwent any form of surgery.

The reposition error means as measured in the sagittal plane (flexion-extension) (1.48˚-1.82˚) are on average higher that what was measured in the frontal plane (left-right lateral flexion) (0.81˚-0.88˚) (Table 1). No significant difference was found between reposition error in the three different positions ($p>0.05$).

Table 1
Lumbar reposition error as tested in the neutral position, and the front foot placement and ball release positions of the delivery stride (n=17)

Outcome variable: reposition error	**Mean (deg)**	**Standard deviation (+-deg)**	**95% confidence interval (deg)**	**Range min, max (deg)**	**Standard error of the mean (deg)**
Neutral lumbar spine: flexion-extension RE	1.82	1.56	1.16-2.37	0.10-6.20	0.38
Neutral lumbar spine: left-right RE	0.85	1.15	0.85-1.74	0.00-4.00	0.28
Front foot placement position: flexion-extension RE	1.49	1.25	0.93-1.91	0.10-4.40	0.30
Front foot placement position: left-right RE	0.81	1.25	0.51-1.05	0.00-2.40	0.17
Ball release position: flexion-extension RE	1.48	1.91	1.43-2.92	0.00-8.00	0.47
Ball release position: left-right RE	0.88	0.81	0.60-1.23	0.10-2.80	0.20

RE – Reposition Error

Table 2
The relationship between lumbar reposition error and injury related variables (n=17)

	Injuries sustained in the past	Past injuries sustained during the bowling action	Low back injuries sustained in the past	Injuries sustained during the cricket season	Injuries sustained while bowling during the cricket season	Low back injuries sustained during the season
	p	**p**	**p**	**p**	**p**	**p**
Neutral lumbar spine: flexion-extension RE	0.01*	0.03*	<0.01*	<0.01*	0.7	0.04*
Neutral lumbar spine: left-right RE	0.62	0.38	0.37	0.52	0.02*	0.33
Neutral lumbar spine: average RE	0.07	0.04*	<0.01*	0.01*	0.26	0.03*
Front foot placement position: flexion-extension RE	0.09	0.33	0.02*	<0.01*	0.98	0.12
Front foot placement position: left-right RE	0.98	0.41	0.03*	0.16	<0.01*	0.26
Front foot placement position: average RE	0.33	0.67	0.01*	0.02	0.19	0.09
Ball release position: flexion-extension RE	0.22	0.15	<0.01*	0.06	0.23	0.07
Ball release position: left-right RE	0.83	0.64	0.03*	0.19	<0.01*	0.12
Ball release position: average RE	0.36	0.55	<0.01*	0.12	0.07	0.12

RE – Reposition Error * Statistically significant ($p<0.05$)

Table 2 shows probability values resulting from statistical tests between groups as defined by the prevalence of different categories of injury. Tests were conducted to establish reposition error values in the neutral position and positions corresponding to front foot placement and ball release of the bowling delivery stride. An increased reposition error was associated with a higher prevalence of low back injuries sustained in the past in the majority of test positions. A high number of previous injuries, injuries sustained during the cricket season under review and injuries sustained during bowling action were also associated with poor reposition sense (Table 2).

Discussion

The aim of this study was to establish the relationship between lumbar position sense and injury related variables. Injuries sustained previously as well as during the cricket season under review were associated with a greater lumbar reposition error. This indicates that these bowlers were not able to reposition their lumbar spines into the initial position after being removed from that position for five seconds. It has been proposed that proprioceptive deficits may lead to abnormal loading across joint surfaces [11], and tissue overload and injury [16; 12]. At the same time, an association has been found between poor proprioception and an increased risk of injury [10; 11]. Low back injury sustained in the past was the injury variable associated with poor reposition sense in most body positions. It may be argued that as a result of their previous injuries, lumbar position sense was decreased, but also that as a result of the decreased lumbar position sense, the bowlers were prone to injury during the season. Thus injury may be both a cause and a consequence of poor proprioception [9].

The reposition error values found in the current study corresponds closely to the results found by Newcomer et al [17], although they are lower to that found by Maduri and Wilson [18]. Maduri and Wilson [18] found an average reposition error of 3.59˚ in healthy individuals when lumbar position sense was tested in three trunk flexion positions. Newcomer et al's [17] results are slightly higher than the results found in the current study, but shows the same trend found in the current study in that the flexion extension reposition error is greater (average 2˚) than the lateral flexion reposition error (average 1.5˚). However both Newcomer et al [17] and Maduri and Wilson [18] tested position sense in one plane at a time while the current study tested reposition sense in two planes (sagittal and frontal) at the same time. A lumbar curvature that is in a position closer to the end of range in a combined movement may result in a lower reposition error than when tested in a neutral lumbar spine position or in a single plane [18]. It is suggested that the tensioning of ligamentous structures and compression on facet joints may play a role in enhancement of proprioception at extreme ranges [19; 18]. The lumbar spine of the pace bowler when positioned in the exact reproduced front foot placement and ball release positions, which involves all three planes, may be put in a position closer to the end of range of motion, thus further away from the neutral lumbar spine position. This may also explain the finding in the current study as well as in that of Maduri and Wilson [18] where a reposition error was high in neutral lumbar spine and decreased as the lumbar curvature moved closer to end of range.

In the current study poor position sense in the neutral lumbar spine position was associated with more injury related variables than position sense in other body positions. The activation of proprioceptors in ligaments and joints in extreme ranges of movement [19] may compensate for poor functioning of muscular proprioceptors in neutral ranges of movement. The neutral lumbar spine position may be a more ideal position to use in the identification of risk to injury, but no evidence to substantiate this statement was found.

Pace bowlers are especially at risk in the presence of proprioceptive deficits as a lack of position sense and associated poor movement control may result in increased passive system end-range loading of the spine during dynamic activity [12]. Although the pace bowlers were pain free on testing day, they may have previously sustained injuries which lead to lumbar segmental instability. Lumbar segmental instability associated with a proprioceptive deficit may have predisposed them to injury during the season [12]. Pinsault et al [20] tested cervical reposition sense in healthy, injury free rugby players and non-rugby players. They found that cervical reposition sense was better in the non-rugby players and argued that participating in rugby may cause minor and asymptomatic cervical spine injuries which lead to proprioceptive deficits and as a result may increase the risk of injury. The same applies to pace bowlers who are required to repetitively perform the pace bowling action during training and matches. Minor and asymptomatic injuries to the low back may lead to proprioceptive deficits. It has also been hypothesised that proprioception decreases in the presence of pain because of a change in normal agonist-antagonist muscle activity [21] and inhibition of local muscles such as lumbar multifidi [22]. Poor lumbar position sense causes bowlers to be prone to injury as their awareness of their lumbar position is decreased and as a result neuromuscular control is decreased [9].

Low back injuries and injuries sustained during the bowling action relate to poor lumbar position sense, as is shown in this study. The low back is especially prone to injury in pace bowlers due to the adaptations resulting from the nature of the pace bowling action, including preferential, asymmetrical hypertrophy of the quadratus lumborum muscle [4], shoulder depression and horizontal flexion strength in the preferred limb, quadriceps strength of the non-preferred limb, increased trunk rotation between back foot and front foot placement phases and a greater ball release height [5; 4]. Poor lumbar position sense can worsen the bowler's predisposition to injury in the presence of these common aspects of the bowling technique. In the light hereof, lumbar proprioception can be improved in order to protect the pace bowler's low back during the high load milieu of the pace bowling action.

The method for measuring lumbar position sense was chosen because of its functional importance. Previously lumbar position sense has been tested in sitting positions [12] because it was argued that vestibular input and lower extremity sensory inputs are greater in a standing position [7]. Here lumbar position sense was tested in standing in order to replicate as many of the components of the pace bowling action as possible, including weight bearing and pelvic position. For this same reason the exact front foot placement and ball release specific positions were also reproduced. Previously lumbar spine reposition error was measured in patients in a neutral lumbar spine position [12], at 20 degrees [23] and at 30 degrees of lumbar flexion [13]. In addition to positioning the bowler's lumbar spine in a functional position (i.e. front foot placement position), reposition error was simultaneously measured in two planes namely sagittal (flexion-extension) as well as frontal (left-right lateral flexion). This multidirectional approach is more functional as normal movement occurs in combined patterns and in more than one plane at the same time. In most studies done in the past, lumbar position sense was measured in one plane at a time [9; 7; 12]. Here, active reposition sense was chosen above passive reposition sense because position sense is enhanced by active repositioning [8]. An added benefit to this study was that the flexible electrogoniometer used provide minimal cutaneous input [12], being extremely sensitive and able to measure in fractions of degrees. Although lumbar proprioception has been assessed in the current study due to the high prevalence of low back injuries in pace bowlers, the greatest contribution to the total range of frontal plane movement (lateral flexion of the trunk) are made by the thoracic spine [24]. This is a limitation of the current study and the assessment

of thoracic proprioception may thus provide valuable results in future research. Further research including a larger sample of non-injured bowlers as well as the assessment of dynamic proprioception may be beneficial.

Funding was granted by the Carnegie Foundation (5500 US$), the National Research Foundation (18900 US$) and the South African Society of Physiotherapy (1050 US$).

Conclusion

Lumbar position sense, as a measure of proprioception, was related to previous injury, injury sustained during the cricket season under review, low back injury in particular as well as injuries sustained during the bowling action. It therefore seems that injury prevention methods are particularly needed due to the high load nature of the pace bowling action. If the proprioception of the lumbar spine can be improved in pace bowlers, their risk of lumbar injury can potentially be reduced. Further research in this area is warranted.

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CHAPTER 4 – Paper 3: Olivier B, Stewart AV, Green AC and McKinon W (submitted 2013) Spinal and Knee Kinematics in Low Back and Lower Limb Injury in Cricket Pace Bowlers, *Journal of Science and Medicine in Sport*

At the time of this thesis submission, paper 3 is under review at the *Journal of Science and Medicine in Sport* as an original article. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article, although general formatting is aligned with the requirements of the specific journal.

1. Original Paper

Title: Cricket pace bowlers: the role of regional spine and knee kinematics in low back and lower limb injury

Authors: Benita Olivier, Andrew Green, Aimee Stewart, Warrick McKinon

Abstract
Objective: The comparison of regional spine and knee kinematics and between injured and non-injured bowlers as measured at the start and end of a cricket season.
Design: Longitudinal observational study.
Method: Regional spine and knee kinematic as well as injury related data of thirty-one injury free, premier league (amateur) pace bowlers were obtained. Injuries were monitored monthly. Pre-and post-season as well as injured and non-injured groups were compared using paired and independent Student's t-tests, respectively.
Results: Sixteen bowlers (51.6%) sustained one or more lower quarter injuries during the course of the eight month cricket season. A difference was found between lumbar spine lateral flexion positioning ($p=0.021$) at the start compared to the end of the season in injured pace bowlers. The range of segmental flexion between front foot placement and ball release at L1 was much greater in the non-injured group than in the injured group as measured at the end of the season ($p=0.031$). Bowlers who did not sustain an injury during the season displayed more flexed knee angles at the start of the season than those who sustained an injury ($p=0.020$).
Conclusions: Cricket pace bowlers are prone to lower quarter (low back and lower limb) injuries. The association between kinematics and lower quarter injuries may exist as a result of altered sensory-motor control strategies (protective mechanisms), may reflect an attempt to increase ball release speeds or may indicate altered trunk load adaptation strategies. This study shows that low back and knee kinematics is associated with and may predict lower quarter injuries in cricket pace bowlers.

Key words: regional spine kinematics, knee kinematics, biomechanics, spine injury, lower limb injury, lower quarter injury, cricket, fast bowlers, pace bowlers, spine lateral flexion, spine extension, spine flexion, spine rotation, knee flexion, knee extension.

1. Introduction

"An 'optimal' pace bowling technique could be defined as one that allows the bowler to bowl fast with a relatively low injury risk".[1] Despite this ideal, studies done in South Africa, Australia, England, West Indies and New Zealand have shown that bowling accounts for more injuries than batting, fielding and wicket keeping. Furthermore, due to the high load nature of the pace bowling action, low back and lower limb injuries are especially common in pace bowlers.[2,3,4]

Studies have assessed the influence of kinematic variables associated with the pace bowling action on low back injury.[5,6,7] Trunk rotation as well as greater trunk left lateral flexion was associated with low back injury.[5,6,7] A more extended knee during the power phase, when ground reaction forces are exceptionally high, was associated with injury.[7,8,9]

Although bowling related kinematic studies have focussed on the association between regional spine and knee kinematics, and low back injury specifically, these studies have not investigated injuries sustained in the lower quarter as a whole – which is low back injuries in combination with lower limb injury.[5,6,7] Due to the kinetic chain connecting all segments of the lower limb to the spine,[10,11] low back dysfunction appears to be associated with lower limb injury.[12,13,14] Putnam[15] explains that the relative angle between segments has a significant effect on the way segments interact in the kinetic chain. The magnitudes and directions of motion-dependent interactive moments are influenced by the angular orientation of the segments involved, which lead to differences in the way these segments interact.[15]

Since lower quarter injuries are extremely common in pace bowlers,[2,3,4] the investigation of all lower quarter injuries, low back as well as lower limb injuries, may provide useful insights. The comparison of kinematics at the start to that at the end of the season and between injured and non-injured players, may give valuable information on the cause and effect of regional spine and knee kinematics during the bowling action. We hypothesise that there will be a difference in kinematic angles as found at the start and at the end of a cricket season as well as between injured and non-injured bowlers.

2. Methods

Injury free, South African premier league (amateur) cricket pace bowlers were invited to participate in the study. Written informed consent was required. Ethical approval was obtained from the associated tertiary institution's human research ethics committee and confidentiality was ensured. Funding for this project was received from the National Research Foundation, the Carnegie Foundation of New York and the local Society of Physiotherapy. These funding organisations played no role in the collection, analysis or interpretation of data and had no right to approve or disprove of the final product of this manuscript.

Injuries (status, nature and prevalence) were monitored through the use of standardised (self-reporting) questionnaires at the start, monthly throughout and at the end of a cricket season. An injury was defined as a "musculoskeletal condition that resulted in loss of at least one day of sporting activity or that occurred during a sporting activity that required medical attention and which forced the bowler to quit the activity".[16,17]

Kinematic variables were assessed at the start and at the end of an eight month cricket season. Kinematic data were captured using five high speed digital cameras (PixeLINK® PL-A741, Ottawa, Ontario) which recorded at 85 frames per second. Cameras were positioned around a

capture volume of 12.76m long, 4.25m wide and 2.08m high. A mean residual error of marker position of less than 1.2mm (±0.7mm) was found from the calibration routine.

Bowlers first warmed-up in their own accustomed manner which included the opportunity to bowl six practice balls. Light reflective markers were attached with double sided adhesive tape (online supplementary material). Each participant bowled six match pace deliveries aimed at a right hand batsman with a new, 156g cricket ball. For each attempt, ball release speed (Stalker ATS®, Texas, USA) and accuracy were measured. Accuracy was determined using a marked target on the pitch[18] as well as second target behind the stumps.[19]

Bowlers who sustained a lower quarter (low back and lower limb) injury during the cricket season under review are referred to as "injured" and those who did not sustain an injury are referred to as "non-injured". The power phase was defined from front foot placement to ball release.[9] The delivery that obtained the highest accuracy score in conjunction with the fastest ball release speed was used for kinematic analysis of variables (online supplementary material). Front foot placement was identified as the first frame when the front (non-dominant) toe marker reached its lowest position. Ball release was defined as the first frame observed where the ball was no longer in contact with the bowler's hand.[20] All data for left hand bowlers have been converted to read as data for right hand bowlers.

Statistical analysis was conducted using Statistica® Version 10 (StatSoft Inc, Tulsa, USA). Data were tested for normality using the Shapiro-Wilk's W test. No violations of the assumption of normality were found. Means and standard deviations, t-values, p-values and confidence intervals were calculated. The differences between kinematic variables, at the start and at the end of the season, and between injured and non-injured groups, were compared by using the paired and independent Student's t-tests, respectively ($p<0.05$). Case wise deletion of comparisons for missing data was performed. Only two of the non-injured and one of the injured bowlers' had instances of missing data. Effect sizes were calculated using Cohen's *d* where effect sizes of 0.2, 0.5 and 0.8 were interpreted as small, medium and large, respectively.[21]

3. Results

Thirty one fast, fast-medium and medium pace bowlers between the ages of 18 and 26 years participated in the study. Twenty six participants were right hand and five were left hand bowlers. Sixteen (51.6%) sustained one or more injuries during the course of the eight month cricket season. All injured pace bowlers sustained at least one spinal and/or lower limb injury during as a direct result of the pace bowling action. Injuries comprised of four low back, four buttock and groin, two hamstring, four knee, one shin and four ankle injuries. All injuries were diagnosed by a qualified physiotherapist.

At the start of the season the spines of bowlers who sustained injuries during the season were positioned in slight lumbar lateral flexion to the right while at the end of the season the spines of bowlers were in slight lateral flexion to the left during front foot placement (Table 1). The lateral flexion range that the spine moves through between front foot placement and ball release at the level of L1 is greater at the start of the season than at the end of the season (Table 1). At the start of the season the shoulder girdle is in a position of extension in relation to the pelvis while at the end of the season it is in a position of flexion at front foot placement (Table 1). Pace bowlers who did not sustain an injury during the season bowled with a more flexed knee angle at the start of the season compared to at the end of the season (Figure 1).

Table 1
The difference between regional spine and knee angles at the start and at the end of the cricket season in pace bowlers who sustained injuries during the season and those who did not

	Injured bowlers (n=16)				Non-Injured bowlers (n=15)			
	Pre-season Mean (SD) (˚)	**Post-season Mean (SD) (˚)**	**p-value**	**Effect size (Cohen's *d*)**	**Pre-season Mean (SD) (˚)**	**Post-season Mean (SD) (˚)**	**p-value**	**Effect size (Cohen's *d*)**
L1 LF at FFP	101.3 (33.3)	74.9 (13.5)	0.021*	1.0	94.3 (31.6)	85.8 (31.8)	0.460	0.3
L1 LF range between BR and FFP	36.7 (32.6)	19.6 (21.2)	0.021*	0.3	48.5 (50.9)	26.4 (25.8)	0.123	0.5
T10 LF at FFP	95.1 (34.4)	72.8 (10.0)	0.047*	0.9	86.7 (27.9)	80.1 (25.6)	0.519	0.2
T7 LF at FFP	92.1 (33.6)	70.5 (8.6)	0.047*	0.9	83.1 (27.2)	76.1 (20.3)	0.425	0.3
Sh-Pelv Flex at FFP	-29.4 (67.4)	39.8 (62.8)	0.023*	1.1	23.5 (39.2)	46.2 (68.6)	0.118	0.4
Knee angle at FFP	163.5 (8.4)	162.1 (12.1)	0.684	0.1	155.4 (12.4)	163.0 (7.5)	0.029*	0.7

BR-ball release; FFP-front foot placement; Flex-flexion; L1-first lumbar vertebra; LF-lateral flexion; SD-standard deviation; Sh-Pelv-Shoulder pelvis; T7-seventh thoracic vertebra; T10-tenth thoracic vertebra; (˚) - degrees
* indicates significant differences between pre-season and post-season ($p<0.05$)
For access to the complete table, view online supplementary material.



Figure 1
The mean knee angle of A) the injured bowlers (164.4˚ flexion) and B) the non-injured bowlers (154.7˚flexion) (p=0.02)

The shoulder girdles of the injured bowlers were in a position of extension while the shoulder girdles of the non-injured bowlers in relation to the pelvis were in a position of flexion at front foot placement (Table 2). At the start of the season, the knee angles of the bowlers that did not sustain injuries were in more flexion than those that did sustain an injury during the season (Table 2). The range of flexion between front foot placement and ball release at L1 is much greater in the non-injured group than in the injured group as measured at the end of the season (Table 2).

Table 2
The difference in regional spine and knee angles between pace bowlers who sustained an injury during the season and those who did not as measured at the start and end of the season

	Pre-season				**Post-season**			
	Non-injured (n=15) Mean SD (˚)	**In-jured (n=16) Mean SD (˚)**	**p-value**	**Effect size (Cohen's *d*)**	**Non-injured (n=15) Mean SD (˚)**	**In-jured (n=16) Mean SD (˚)**	**p-value**	**Effect size (Cohen's *d*)**
L1 Flex range between BR and FFP	40.5 (44.0)	20.1 (18.0)	0.097	0.6	36.7 (35.2)	15.2 (10.1)	0.031 *	0.8
Sh-Pelv Flex at FFP	29.3 (44.0)	-27.2 (65.7)	0.009 *	1.0	46.2 (68.6)	39.8 (62.8)	0.797	0.1
Sh-Pelv LF at FFP	10.1 (30.1)	-11.1 (35.0)	0.082	0.6	-1.9 (19.9)	-17.0 (10.8)	0.016 *	0.9
Knee angle at FFP	154.7 (11.5)	164.4 (8.7)	0.020 *		162.8 (10.8)	162.8 (11.9)	0.998	0.0

BR-ball release; FFP-front foot placement; Flex-flexion; L1-first lumbar vertebra; LF-lateral flexion; SD-standard deviation; Sh-Pelv-Shoulder pelvis; **(˚)** - degrees
* indicates significant differences between non-injured and injured ($p<0.05$)
For access to the complete table, view online supplementary material.

4. Discussion

The injured bowlers in this study were still in a position of slight trunk lateral flexion to the right by the start of the power phase (at front foot placement), while their healthy counterparts here, as well as in Ferdinands and colleagues'[9] study, were in left lateral flexion. Ferdinands and colleagues[9] found that earlier in the delivery phase, slight lateral flexion to the right is evident, but by the start of the power phase active lateral flexion to the left is expected. This may indicate a delay in the sequence of movement of the spine during the phases of the bowling action amongst bowlers prone to injury. Cholewicki et al[22] found an 8 millisecond delay in lateral flexor muscle response to be predictive of low back injury, which is significant considering that the average time that the bowlers in this study used to progress

from front foot placement to ball release was 52.9milliseconds. This delay may be a pre-existing risk factor rather than the effect of low back injury[22,23,24] and was not found amongst the bowlers who did not sustain an injury during the cricket season.

In addition to the kinetic link between the spine and the lower limbs, sensory-motor control of the spine is also known to affect injury risk of the lower limb.[12,24] The utilisation of this larger range of lateral flexion motion at L1 motion at the start of the season compared to the end of the season may be seen as predisposing to injury. It may also indicate that the injured pace bowler is protecting his spine by decreasing the range of movement at the end of the season, after injury was sustained during the season. The motor control may have been affected by injury, which now may influence the movement of the lumbar spine. The opposite may also be true where motor control was already affected; large movements occurred due to a decrease in control, injury occurred in the kinetic chain of the lower limb and at the end of the season, a protective mechanism may have been activated which decreased the amount of movement that takes place between front foot placement and ball release.[25,26,27] If this large range of lateral flexion is associated with low back pathology,[5] it may be seen as a predictive factor for low back injury during the season, as shown in this study.

The decrease in range of spinal movement at the end of the season can be explained by three theories. Firstly, the fear-avoidance model states that an individual's fear of movement may lead to avoidance of movements or positions that typically increase pain.[25] Secondly, the pain-adaptation model suggests that pain afferent activity decreases activity in a muscle that is responsible for moving a joint into a pain-provoking position and increases the activity of the muscle antagonists, which leads to a decrease in velocity and limits excursions, and protection against pain.[26] Thirdly, Mishra et al[27] found an association between a haplotype gene in the GABA-β1 receptor subunit and motor limitation scores suggesting that this gene plays a role in pain-related reduction of movement. Furthermore, flexion and extension adaptation strategies of the trunk changed the shear forces on the knee.[11] The same may be true for lateral flexion of the trunk in an attempt to decrease shear forces on the lower limb by decreasing the amount of asymmetrical trunk movement.

Based on the results found in this study, global spinal extension may predict injury, while flexion may indicate the need to protect the spine. Kulas et al[11] found that when the a load is placed on the trunk, in cases where an extension trunk adaptation strategy was used, anterior knee shear was increased, while a flexion adaptation strategy had the opposite effect and may serve as a protective strategy. The greater range of flexion in the non-injured group at the end of the season, may indicate a protective mechanism where the injured pace bowler attempts to decrease the spinal range of movement to control associated movements in the kinetic chain.[25,26,27] Parnianpour et al[28] found a decline in sagittal plane motion, indicating a tendency towards task aversion, in the presence of fatigue which may be applicable to the bowlers in this study.

A more extended front knee, even by only seven degrees, may be a predisposing factor to injury rather than the result of injury. This is most probably due to better dissipation of ground reaction forces by a flexed limb.[7] Overuse and/or microtrauma during the season may affect the ability to bowl with a more flexed leg, because of fatigue of other systems. For example, Portus et al[7] found that increased trunk stability is associated with the ability to bowl with a more flexed leg. If trunk stability was affected during the season due to spinal microtrauma suffered as a result of the high load repetitive bowling action,[9] this may affect

the knee angle. Thus, the influences on one end of the kinetic chain may affect changes in another.[15]

A limitation of this study as well as that of numerous other kinematic studies is that skin markers were used which introduces its own set of errors in estimating spinal movements. In the future, methods to directly measure spinal movements may be developed which would better describe the variables inferred in this study. Furthermore, the low sampling rate of 85Hz can be improved upon in future studies. In interpreting the findings from the current paper, it should be taken into account that any change in the kinematics of the pace bowling action should not be made without considering the kinetics (load and force) associated with it.

5. Conclusion

Low back and knee kinematics, as found in the power phase of the pace bowling action, is associated and may predict lower quarter injuries in cricket pace bowlers. Differences found between injured and non-injured groups may be ascribed to altered sensory-motor control strategies, protective mechanisms and altered trunk load adaptation strategies. Future research is indicated to establish the association between spinal kinetics and lower limb injuries.

6. Practical implications

- Low back dysfunction appears to be associated with lower limb injury, due to the kinetic chain connecting all segments of the lower limb to the spine.
- The decrease in range of spinal movement at the end of the season can be explained by three theories, namely the fear-avoidance model, the pain-adaptation model and a gene plays a role in pain-related reduction of movement.
- Global spinal extension may predict injury, while flexion may indicate the need to protect the spine due to trunk adaptation strategies.
- A more extended front knee, even by only seven degrees, may be a predisposing factor to injury rather than the result of injury.

7. Acknowledgments

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9. Supplementary material
Detailed tables 1 and 2 as well as Figure 2:

Table 1
Description of regional spine and knee kinematic variables*

L1, T10, T7 LF	Lateral flexion refers to lateral flexion of L1, T10 and T7 in relation to the pelvis (90˚ indicates upright standing, neutral position; <90˚ indicates lateral flexion to the left; >90˚ indicates lateral flexion to the right). Lateral flexion angles were calculated as the angle between the pelvis plane (transverse plane, established by the limits of sacral and left and right anterior superior iliac spines markers) and the plane to the relevant markers along the sagittal plane (established by the limits of sacral, midpoint between the anterior superior iliac spines markers, and one of L1, T10 and T7 markers).
L1, T10, T7 Flex	Flexion refers to the planar flexion angle between the different segments namely L1 flexion (angle between T10, L1 and S1); T10 flexion (angle between T7, T10 and L1); T7 flexion (angle between C7, T7 and T10). A flexion/extension angle <180˚indicates spinal flexion; an angle >180˚ indicates spinal extension.
L1, T10, T7 LF/Flex range between BR and FFP	Lateral flexion or flexion range between ball release and front foot placement was calculated by subtracting the angle calculated at ball release from the angle calculated at front foot placement.
Sh-Pelv Flex	Shoulder girdle position in relation to pelvic position was defined as positive for flexion, lateral flexion to the left and rotation to the left. A XYZ (flexion, adduction, rotation) Cardan rotation sequence was used to calculate the relative movement of the pelvis and shoulder girdles, using independent established reference frames for the respective girdles. The relative motion of the shoulders to the pelvis was calculated as the difference in the specific rotation angle.
Sh-Pelv LF/Flex/Rot range between BR and FFP	Shoulder girdle position in relation to pelvic position range between ball release and front foot placement was calculated by subtracting the angle calculated at ball release from the angle calculated at front foot placement.
Knee angle	The planar flexion/extension angle was measured in the sagittal plane where an angle of 180˚ presents a straight knee and an angle of <180˚ presents a flexed knee.
Knee angle range between BR and FFP	The knee angle range between ball release and front foot placement was calculated by subtracting the knee angle at ball release from the knee angle at front foot placement.

*Kinematic variables were extracted at front foot placement and ball release, and are presented as degrees (˚).

Table 2
The difference between spinal and knee angles at the start and at the end of the cricket season in pace bowlers who sustained injuries during the season and those who did not

	Injured bowlers (n=16)			Non-Injured bowlers (n=15)		
	Pre-season Mean (SD) (˚)	**Post-season Mean (SD) (˚)**	**p-value**	**Pre-season Mean (SD) (˚)**	**Post-season Mean (SD) (˚)**	**p-value**
L1 LF at FFP	101.274 (33.340)	74.883 (13.530)	0.021*	94.348 (31.556)	85.775 (31.847)	0.460
L1 LF at BR	79.358 (20.943)	76.005 (22.353)	0.572	101.822 (43.983)	81.149 (22.792)	0.170
L1 LF range between BR and FFP	36.659 (32.641)	19.571 (21.207)	0.021*	48.519 (50.940)	26.350 (25.780)	0.123
T10 LF at FFP	95.085 (34.413)	72.727 (9.975)	0.047*	86.654 (27.908)	80.068 (25.640)	0.519
T10 LF at BR	74.558 (16.362)	75.882 (23.039)	0.809	96.020 (42.723)	79.495 (22.448)	0.239
T10 LF range between BR and FFP	33.400 (33.365)	18.781 (17.278)	0.069	41.259 (49.374)	25.835 (27.463)	0.199
T7 LF at FFP	92.070 (33.590)	70.464 (8.645)	0.047*	83.110 (27.181)	76.057 (20.291)	0.425
T7 LF at BR	73.690 (16.510)	74.124 (23.934)	0.940	92.627 (44.482)	77.322 (24.966)	0.305
T7 LF range between BR and FFP	29.961 (32.925)	18.362 (17.043)	0.164	43.154 (50.112)	24.518 (21.891)	0.129
L1 Flex at FFP	152.841 (15.429)	152.371 14.938)	0.930	140.021 (26.809)	138.716 (21.664)	0.878
L1 Flex at BR	151.874 (21.900)	161.219 (13.213)	0.146	158.027 (18.981)	168.753 (5.109)	0.091
L1 Flex range between BR and FFP	20.588 (18.495)	15.203 (10.072)	0.381	36.057 (41.938)	36.714 (35.224)	0.938
T10 Flex at FFP	161.608 (27.560)	165.368 (9.566)	0.653	164.827 (13.876)	164.140 (12.268)	0.901
T10 Flex at BR	158.201 (21.826)	162.909 9.504)	0.425	162.756 (8.053)	165.289 (9.038)	0.556
T10 Flex range between BR and FFP	9.219 (10.139)	11.137 (9.147)	0.593	28.802 (47.774)	22.036 (41.780)	0.436
T7 Flex at FFP	151.023 (11.249)	144.390 (18.723)	0.253	152.767 (17.079)	149.730 (10.508)	0.524
T7 Flex at BR	145.044 (20.673)	149.768 14.879)	0.462	147.613 (31.819)	146.219 (26.216)	0.884
T7 Flex range	17.344	10.681	0.126	33.070	24.637	0.166

between BR and FFP	(13.097)	(8.859)		(43.791)	(38.602)	
Sh-Pelv Flex at FFP	-29.407 (67.408)	39.835 (62.820)	0.023*	23.461 (39.197)	46.185 (68.602)	0.118
Sh-Pelv Flex at BR	22.238 (42.620)	33.937 (46.721)	0.521	24.731 (52.224)	37.625 (61.521)	0.620
Sh-Pelv Flex range between BR and FFP	69.872 (70.346)	66.979 (58.120)	0.896	54.658 (26.949)	65.251 (45.034)	0.404
Sh-Pelv LF at FFP	-12.729 (35.636)	-17.006 (10.771)	0.642	8.394 (30.464)	-1.932 (19.919)	0.255
Sh-Pelv LF at BR	35.515 (28.060)	28.725 (26.778)	0.483	24.661 (24.973)	22.174 (26.703)	0.782
Sh-Pelv LF range between BR and FFP	49.211 (33.519)	49.415 (19.787)	0.980	32.672 (19.424)	34.330 (28.492)	0.863
Sh-Pelv Rot at FFP	2.127 (36.445)	30.937 (27.250)	0.059	-3.239 (30.084)	12.674 (31.063)	0.139
Sh-Pelv Rot at BR	24.777 (42.377)	32.032 (60.344)	0.686	-7.307 (54.867)	30.393 (61.206)	0.056
Sh-Pelv Rot range between BR and FFP	163.532 (8.412)	162.106 (12.089)	0.684	41.167 (39.552)	49.860 (36.455)	0.494
Knee angle at FFP	163.532 (8.412)	162.106 (12.089)	0.684	155.357 (12.400)	162.978 (7.530)	0.029*
Knee angle at BR	140.227 (19.542)	128.476 (15.145)	0.223	142.645 (20.875)	137.918 (18.061)	0.485
Knee angle range between BR and FFP	36.893 (44.509)	32.435 (18.397)	0.782	18.314 (13.157)	29.121 (9.499)	0.099

BR-ball release; FFP-front foot placement; Flex-flexion; L1-first lumbar vertebra; LF-lateral flexion; SD-standard deviation; Sh-Pelv-Shoulder pelvis; T7-seventh thoracic vertebra; T10-tenth thoracic vertebra

* indicates significant differences between pre-season and post-season ($p<0.05$)

Table 3
The difference in spinal and knee angles between pace bowlers who sustained an injury during the season and those who did not as measured at the start and end of the season

	Pre-season			Post-season		
	Non-injured (n=15) Mean SD	**Injured (n=16) Mean SD**	**p-value**	**Non-injured (n=15) Mean SD**	**Injured (n=16) Mean SD**	**p-value**
L1 LF at FFP	92.977 (30.868)	98.846 (33.642)	0.617	85.775 (31.847)	74.883 (13.53)0	0.235
L1 LF at BR	103.931 (42.792)	79.758 (20.296)	0.055	82.101 (22.090)	76.005 (22.353)	0.476
L1 LF range between BR and FFP	48.982 (49.120)	35.826 (31.710)	0.380	26.350 (25.780)	19.571 (21.207)	0.445
T10 LF at FFP	85.903 (27.049)	93.550 (33.808)	0.494	80.068 (25.640)	72.727 (9.975)	0.312
T10 LF at BR	96.740 (41.135)	74.880 (15.860)	0.059	86.674 (34.448)	75.882 (23.039)	0.327
T10 LF range between BR and FFP	40.555 (47.656)	31.887 (32.797)	0.558	25.835 (27.463)	18.781 (17.278)	0.412
T7 LF at FFP	82.565 (26.278)	90.685 (32.921)	0.456	76.057 (20.291)	70.464 (8.645)	0.337
T7 LF at BR	97.024 (45.795)	73.790 (15.955)	0.067	77.322 (24.966)	74.124 (23.93)4	0.732
T7 LF range between BR and FFP	45.561 (49.180)	28.426 (32.396)	0.258	24.518 (21.891)	18.362 (17.043)	0.404
L1 Flex at FFP	141.747 (26.684)	152.185 (15.135)	0.187	138.716 (21.664)	152.371 (14.938)	0.057
L1 Flex at BR	150.703 (32.056)	152.087 (21.175)	0.890	168.340 (5.113)	161.219 (13.213)	0.080
L1 Flex range between BR and FFP	40.525 (43.962)	20.110 (17.970)	0.097	36.714 (35.224)	15.203 (10.072)	0.031*
T10 Flex at FFP	164.587 (13.403)	161.702 (26.628)	0.709	164.140 (12.268)	165.368 (9.566)	0.765
T10 Flex at BR	152.526 (37.680)	159.193 (21.455)	0.554	164.861 (8.789)	162.909 (9.504)	0.579
T10 Flex range between BR and FFP	35.646 (53.122)	9.328 (9.805)	0.061	22.036 (41.780)	11.137 (9.147)	0.333
T7 Flex at FFP	154.248 (17.429)	151.193 (10.889)	0.560	149.730 (10.508)	144.390 (18.723)	0.357
T7 Flex at BR	139.444 (43.231)	144.527 (20.079)	0.676	146.219 (26.216)	149.768 (14.879)	0.658
T7 Flex range	40.316	17.321	0.089	24.637	10.681	0.184

between BR and FFP	(50.676)	(12.653)		(38.602)	(8.859)	
Sh-Pelv Flex at FFP	29.265 (43.954)	-27.160 (65.739)	0.009*	46.185 (68.602)	39.835 (62.820)	0.797
Sh-Pelv Flex at BR	19.534 (53.811)	21.015 (41.464)	0.933	37.625 (61.521)	33.937 (46.721)	0.859
Sh-Pelv Flex range between BR and FFP	61.584 (37.334)	65.747 (69.934)	0.839	65.251 (45.034)	66.979 (58.120)	0.930
Sh-Pelv LF at FFP	10.064 (30.060)	-11.113 (35.030)	0.082	-1.932 (19.919)	-17.006 (10.771)	0.016*
Sh-Pelv LF at BR	22.063 (25.889)	36.043 (27.191)	0.162	22.174 (26.703)	28.725 (26.778)	0.524
Sh-Pelv LF range between BR and FFP	33.505 (18.994)	48.062 (32.707)	0.144	34.330 (28.492)	49.415 (19.787)	0.107
Sh-Pelv Rot at FFP	2.714 (37.041)	3.767 (35.815)	0.936	12.674 (31.063)	30.937 (27.250)	0.103
Sh-Pelv Rot at BR	0.821 (60.860)	23.197 (41.425)	0.244	30.393 (61.206)	32.032 (60.344)	0.944
Sh-Pelv Rot range between BR and FFP	39.784 (38.487)	48.799 (44.042)	0.550	49.860 (46.2)	61.719 (47.198)	0.458
Knee angle at FFP	154.743 (11.453)	164.420 (8.738)	0.020*	162.8 (10.8)	162.815 (11.914)	0.998
Knee angle at BR	138.161 (21.429)	143.647 (19.471)	0.537	141.694 (18.2)	130.705 (17.108)	0.146
Knee angle range between BR and FFP	22.287 (14.362)	33.070 (41.255)	0.442	24.237 (15.0)	31.326 (16.462)	0.244

BR-ball release; FFP-front foot placement; Flex-flexion; L1-first lumbar vertebra; LF-lateral flexion; SD-standard deviation; Sh-Pelv-Shoulder pelvis; T7-seventh thoracic vertebra; T10-tenth thoracic vertebra

* indicates significant differences between non-injured and injured ($p<0.05$)

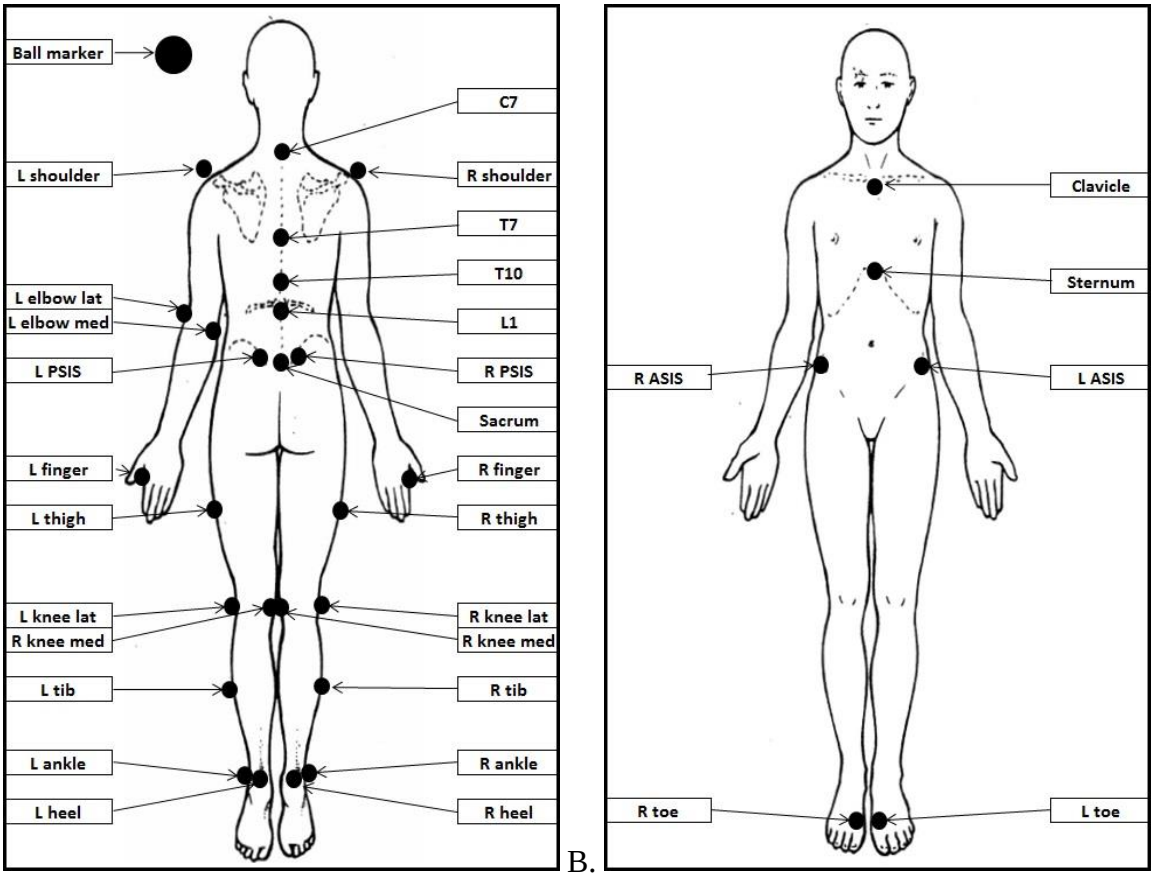

Figure 1

Light reflective marker placement: A. Posterior view; B. Anterior view

2. Linking Notes between Chapters 2, 3 and 4 (Papers 1, 2 and 3)

This section contains information to clarify the link between Chapters 2, 3 and 4 (Papers 1, 2 and 3). In depth discussions in findings of individual papers are in the discussion sections of each paper, while an overall discussion follows in Chapter 8.

The studies conducted in Chapters 2, 3 and 4 contain data on various intrinsic factors and their association with injury. In Chapters 2 and 3 intrinsic factors (static balance, dynamic balance and lumbar proprioception) were found to be associated with injury, while these same intrinsic factors have been associated with increased performance in studies in other sports. These intrinsic factors thus have the potential to prevent injury while at the same time optimise performance. The same technique-related intrinsic factors associated with injury as described in Chapter 4, are often associated with improved performance, specifically faster ball release speed (Chapter 5).

Chapters 2 and 3 contain an example of different methods of investigating intrinsic factors and the relationship with injury. Chapter 2 compares variables (static balance, dynamic balance and lumbo-pelvic movement control) measured at the start of the season with measurements at the end of the season, while Chapter 3 establishes a relationship between lumbar proprioception and injury-related variables (previous injury, injury sustained during the cricket season under review, injuries specifically sustained during the bowling action and those specific to the low back) where injuries were followed up throughout the season. Chapters 2 and 3 both explore components of neuromuscular control which play an inherent role in movement, while Chapter 4 explores the movements as part of the bowling action. The same definition of injury was used for all three papers (Chapters 2, 3 and 4).

CHAPTER 5 – Paper 4: Olivier B, Stewart AV, Green AC and McKinon W (submitted in 2013) Cricket Pace Bowling: A Longitudinal Study of Spinal and Knee Kinematics, Ball Release Speed and Bowling Accuracy, *Journal of Science and Medicine in Sport*

At the time of this thesis submission, this chapter is under review at the journal, *Journal of Science and Medicine in Sport,* as an original article. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article, although general formatting is aligned with the requirements of the specific journal.

1. Original Paper

Title: Cricket pace bowling: a longitudinal study of regional spine and knee kinematics, ball release speed and bowling accuracy

Authors: Benita Olivier, Andrew Green, Aimee Stewart, Warrick McKinon

Abstract
Objectives: To establish the relationship between pace bowling performance and regional spine and knee kinematics as analysed at the start and at the end of a cricket season.
Design: Longitudinal observational design.
Method: Regional spine and knee kinematics were analysed in 31 injury free, premier league (amateur) cricket pace bowlers over the age of 18 years. Performance measures, namely ball release speed and accuracy were captured. Pearson's correlation coefficient, ANOVA and Tukey's *post hoc* comparisons were used to analyse relationships between kinematic and performance (ball release speed and accuracy) before and after a cricket season.
Results: A more extended knee angle (r=0.404; p=0.037), a larger arm to thorax angle (r=0.504; p=0.004), a more upright global trunk position (r= -0.3668; p=0.046), more global trunk left lateral flexion (r=0.362; p=0.045), larger L1 (r= -0.450; p=0.011), T10 (r= -0.467; p=0.008), T7 (r= -0.509; p=0.003) segmental spinal lateral flexion and more global trunk left rotation (r=0.411; p=0.022) were correlated with higher ball release speeds at the start of the season. A larger arm to thorax angle (r=0.448; p=0.015) and a smaller change in knee angle between FFP and BR was associated with higher ball release speed at the end of the season.
Conclusions: Most statistically significant relationships were found at the start of the season, when all bowlers were injury free which may have resulted in clear associations, while the incidence of injury, micro-trauma or overuse during the cricket season may have altered the bowling technique as a result of fear-avoidance or pain-adaptation protective strategies.

***Key words*:** sport; fast bowler; pace bowler; performance; biomechanics; bowling technique

1. Introduction

Ball release speed and bowling accuracy are two variables that are crucial to the performance of a pace bowler. A batsman has only a few milliseconds to judge the flight of the ball if a high ball release speed is successfully achieved. In addition to high ball release speeds, if a pace bowler can predict the pitch of the ball, such accuracy affords him a useful tool allowing him to strategically plan the dismissal of a batsman.

The relationship between technique-related three dimensional kinematics of the pace bowling action and ball release speed has been widely investigated in once off cross-sectional studies. Front knee angle at front foot placement and ball release has been found to be associated with higher ball release speeds.[1] In addition, a more extended knee contributes to higher ball release speed by increasing the radial distance between front foot contact and the extended bowling arm, which results in a greater tangential end point velocity.[2] There is still, however, controversy around the relationship between ball release height and ball release speed.[3] Furthermore shoulder counter-rotation and shoulder orientation in the transverse plane is known to be associated with faster ball release speed.[1,3]

Studies investigating the association between bowling accuracy and technique-related variables are scarce.[4,5] In addition, the current authors could not find any research where the movement of specific, regional spinal segments (T7, T10, L1), around which much of the bowling action is centred, have been assessed as contributors to bowling performance. Finally, the rarity of longitudinal studies assessing technique-related variables and their possible contribution to speed and accuracy prompted the current study. Therefore the aim of this study is to investigate the relationship between regional spine and knee kinematics of the pace bowling action and performance variables, namely speed and accuracy, at the start as well as at the end of a cricket season.

2. Methods

Injury free, premier league (amateur) cricket pace bowlers over the age of 18 years were invited to participate in this study. Ethical clearance was obtained from the associated tertiary institution's human research ethics committee in the spirit of the Helsinki Declaration.

Ball release speed was captured using a hand held radar gun (Stalker ATS®, Texas, USA) positioned 180˚ behind the ball release point.[3] Classification of bowlers according to speed was as follows: medium (120–130 km/h); medium fast (130–140 km/h) and fast (>140 km/h).[6]

Bowling accuracy was assessed according to a categorical scale where the ability to pitch the ball in both target blocks (see online supplementary material) gave an accuracy score of 2. If a bowler pitched the ball in one or none of the two target blocks, he obtained a score of 1 or 0 out of 2, respectively.[5,7] Each bowler bowled six match pace deliveries with a new 156g cricket ball (Kookaburra® Sport Ltd, JRT Crampton Pty, Durban).

Five high speed digital cameras (PixeLINK® PL-A741, Ottawa, Ontario) recording at 85 frames per second, were used. A capture volume of 12.76m long, 4.25m wide and 2.08m high was created and allowed for the full delivery action and initial ball flight to be captured. Calibration of the measurement volume was performed prior to each bowler's data capture. A mean residual error of marker position of less than 1.2mm (±0.7mm) was determined during the calibration.

Kinematic and performance variables were assessed at the start and again at the end of an eight month cricket season. Bowlers were given time to warm up in their own accustomed way before the actual testing procedure. Light reflective markers were attached to predetermined anatomical sites (see online supplementary material). Participants bowled six match pace deliveries aimed at a right hand batsman.

Kinematic angles were determined at front foot placement and ball release, and were presented as degrees (˚). Front foot placement was identified as the first frame when the front (non-dominant) toe marker reached its lowest position. Ball release was defined as the first frame observed where the ball was no longer in contact with the bowler's hand.[3] All data for left hand bowlers were converted to read as data for right hand bowlers. Case wise deletion of comparisons were performed where data were missing (the sample size is therefore reflected for each comparison in the results section).

Data were analysed using Statistica® Version 10 (StatSoft Inc, Tulsa, USA). Parametric tests were employed as all data were found to be normally distributed after being assessed with the Shapiro-Wilk's W test.

Pearson's product moment correlation coefficient (r) was used to identify relationships between continuous variables (kinematic variables and ball release speed). Qualitative descriptions for the strength of the relationships were used to contextualise the relationships between continuous variables as follows: r=0.00-0.25 little or no relationship; r=0.25-0.50 fair relationship; r=0.50-0.75 moderate to good relationship; r>0.75 good to excellent relationship.[8]

The relationship between kinematic variables, ball release speed (continuous data) and bowling accuracy (categorical data) were analysed using a one way ANOVA. Tukey's *post hoc* comparisons were performed in case of significant main ANOVA effects. Pearson Chi-squared test was used to analyse the relationship between knee angle classification category and accuracy (categorical data). Statistical significance was defined as $p<0.05$. Knee angles were classified into four different groups depending on the angle at front foot placement and ball release: flexor - knee flexion 10° or more followed by less than 10° of knee extension; flexor-extender - flexion and extension of the knee by 10° or more; extender - knee flexion less than 10° followed by knee extension by 10° or more; constant brace - both flexion and extension of the knee less than 10°.[1]

3. Results

Twenty six right hand and five left hand dominant fast, fast-medium and medium pace bowlers between the ages of 18 and 26 years participated in this study. A fair relationship was found where the straighter the knee (closer to 180˚) was associated with a faster ball release speed. Where the arm to thorax angle is larger, (arm is more to the right of the thorax) the ball release speed was faster (moderate relationship). A fair relationship between a smaller global trunk flexion angles (shoulder girdle relative to the pelvis) as well as a smaller change in global trunk flexion angle between front foot placement and ball release was associated with faster ball release speeds. More global trunk lateral flexion as well as rotation to the left resulted in a faster ball release speed. Lateral flexion to the left at the segmental levels of L1, T10 and T7 at front foot placement also gave rise to higher ball release speeds (Table 1).

Table 1
The relationship between kinematic variables and ball release speed as measured at the start and end of the cricket season

Kinematic Variable	Correlation coefficient (r)	Number of bowlers (n)	p-value
Start of the season			
Knee angle at FFP	0.404	27	0.037*
Arm to thorax angle at FFP	0.504	31	0.004*
Sh-Pelv Flex at BR	-0.367	30	0.046*
Sh-Pelv Flex range between BR and FFP	-0.398	30	0.029*
Sh-Pelv LF at FFP	0.362	31	0.045*
Sh-Pelv LF at BR	0.464	30	0.010*
Sh-Pelv Rot at FFP	0.411	31	0.022*
L1 LF at FFP	-0.450	31	0.011*
T10 LF at FFP	-0.466	31	0.008*
T7 LF at FFP	-0.509	31	0.003*
End of the season			
Change in knee angle between FFP and BR	-0.457	23	0.028*
Arm to thorax angle at FFP	0. 448	29	0.015*

Arm to thorax angle refers to the angle of the arm (shoulder joint to ball) relative to the thorax (0- arm is parallel to thorax; negative arm is more to the left of thorax; positive are to the right of thorax)
Sh-Pelv Flex refers to shoulder girdle flexion in relation to the pelvis- positive value indicates flexion
Sh-Pelv LF refers to shoulder girdle lateral flexion in relation to the pelvis- positive value indicates lateral flexion to the left
Sh-Pelv Rot refers to shoulder girdle rotation in relation to the pelvis- positive value indicates rotation to the left
LF refers to lateral flexion of L1/T10/T7 in relation to the pelvis (90˚-upright standing, neutral position; <90˚-lateral flexion to the left; >90˚-lateral flexion to the right)
BR-ball release; FFP-front foot placement
* indicates statistical significance ($p<0.05$)

At the end of the cricket season, fewer statistically significant relationships between kinematic variables and ball release speed were found. The smaller the change in knee angle between front foot placement and ball release, the higher the ball release speed. Ball release speed was also higher when the arm was more to the right of the thorax. No statistically significant relationship was found between any of the regional spine angles and ball release speed.

No statistically significant relationship was found between kinematic variables and accuracy as measured at the start and at the end of the cricket season. A statistically significant relationship was established between knee angle classification categories and accuracy at the start of the season (Figure 1 and 2).

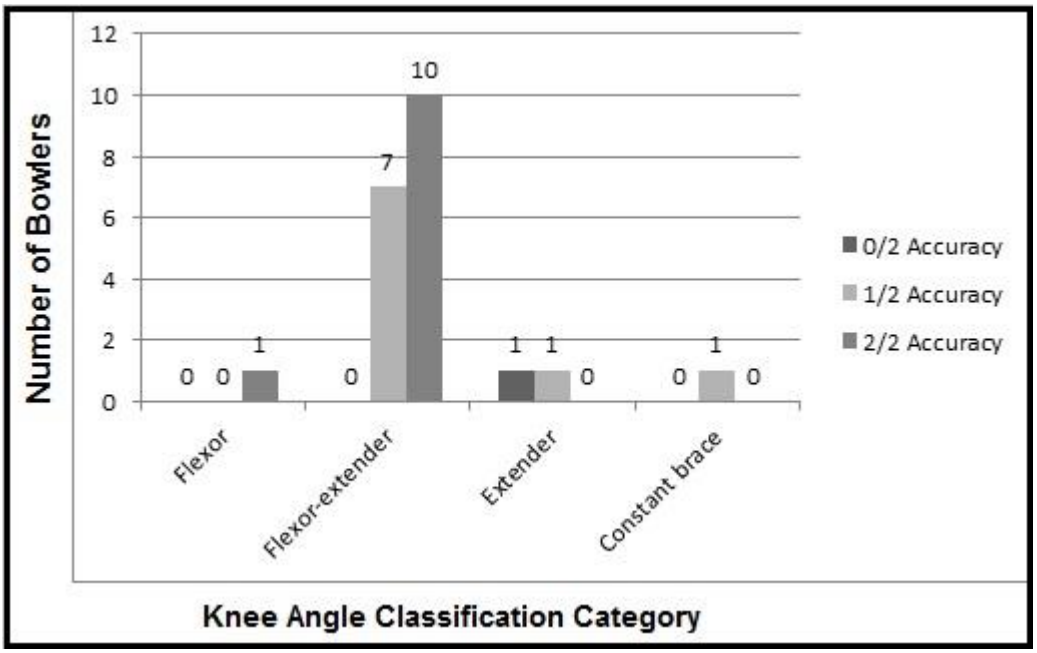

Figure 1 – The relationship between knee angle classification category and bowling accuracy at the start of the season (n=21) (p=0.045).

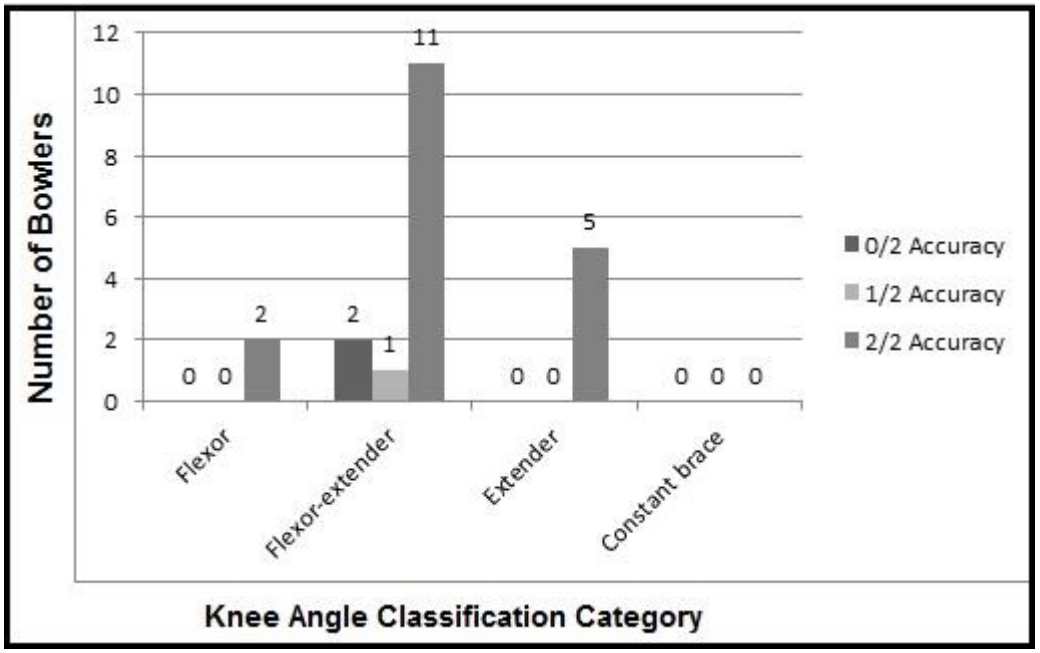

Figure 2 – The relationship between knee angle classification category and accuracy at the end of the season (n=21) (p=0.78).

At the start of the season, no significant difference (p=0.88) in bowling speed between an accuracy score of 0 (123.7 ± 15 km/hr), 1 (125.96 ± 5km/hr) and 2 (124.87 ± 6km/hr) was found. At the end of the season, a statistically significant difference (p=0.034) in bowling speed between an accuracy score of 0 (116.99 ± 13 km/hr), 1 (137.86 ± 10km/hr) and 2 (124.08 ± 4km/hr) was found. Tukey's *post hoc* comparisons revealed a difference between the average speed bowled by those that scored 0/2 (123.17km/hr) and those that scored 1/2 (125.96km/hr) for accuracy.

4. Discussion

A front knee angle closer to 180˚ (which denotes a straighter knee) at front foot placement was correlated with faster ball release speeds (Table 1). Portus et al[1] suggests that a straighter knee has the capacity to transfer kinetic energy more efficiently to the ball and in that way facilitates higher ball release speeds. The body actions which result in higher ball release speeds (enhanced performance) have raised concerns for health professionals where the increased strain on the body which results in greater performance also increase the likelihood of injury. A key example of this is where the knee angle associated with increased ball release speed is also associated with injury.[1,9] A straighter knee at front foot impact is associated with injury due to the increase in impact forces[10] and a decrease in the time to peak force.[2] Due to this association with injury, it may be ideal for pace bowlers to flex their knees at front foot placement and extend their knees to more than 150˚ at ball release.[2] This technique characteristic was only present in five bowlers in this study, and was also found to be a rare phenomenon by Bartlett et al,[2] probably because the extension angle at front foot placement and not only at ball release is associated with higher ball release speed, as found in this study.

A smaller change in knee angle between front foot placement and ball release was associated with higher ball release speeds (Table 1), which is similar to Wormgoor et al's[3] finding. Bartlett et al,[2] Portus et al[1] and Wormgoor et al[3] associated the flexor-extender front leg knee action classification with performance benefits. In this study, most bowlers who obtained an accuracy score of 2/2 were in the flexor-extender group, which means "flexion and extension of the knee by 10° or more" between front foot placement and ball release (Figure 1 and 2). This indicates that the most accurate bowlers' knees were at an angle of less than 170˚ at both front foot placement and ball release. While speed may be associated with an extended knee, it seems likely that accuracy is associated with a slightly more flexed knee. None of the other kinematic variables were associated with accuracy, however, at the end of the season speed and accuracy were found to be inversely related. The fastest bowlers scored an average accuracy grading, while those who scored a zero as well as those who scored 2/2 bowled at a slower pace.

At the start as well as at the end of the cricket season, a larger arm to thorax angle was associated with higher ball release speeds at front foot placement (Table 1). At front foot placement the bowling arm is usually elevated to the level of the shoulder, also called "arm-horizontal".[7] If the arm is in a position more to the right of the trunk, more internal rotation until ball release is possible. More internal rotation is associated with higher flexion and extension elbow angles (throwing) and subsequently an increase in ball release speed.[11] In this study, elbow angles of the bowling arm were not measured. Bowlers may have attempted to increase ball release speed by increasing the arm to thorax angle, which consequently increase the amount of shoulder internal rotation and elbow flexion and extension. Furthermore, at arm horizontal position, bowlers are usually at a more front-on position.[7] A more front-on position was also associated with more elbow flexion and extension during the swing phase, and again, higher ball release speeds.[7]

In this study, faster ball release speeds were associated with a smaller global trunk flexion angle (shoulder girdle in relation to the pelvis) at ball release, as well as with a smaller change in global trunk flexion angle between front foot placement and ball release (Table 1). Bowlers may attempt to construct a more extended upper body in order to increase ball release height, which may suggest that a large amount of trunk flexion will occur during the follow through phase to dissipate the large amount of flexion torque.[10]

Global trunk lateral flexion as well as L1, T10 and T7 segmental lateral flexion to the left was correlated with faster ball release speeds (Table 1). Ferdinands et al[10] found that not only lumbar flexion, but also lumbar lateral flexion occurs actively in the lumbar spine as torque and power values are in the same direction, which actuates the trunk muscles. Lateral flexion may in other words be responsible for higher ball release speeds due to high activity in the trunk musculature. Pace bowlers utilise a large amount of trunk lateral flexion to the contra-lateral side, thus left side in a right handed bowler, especially at front foot placement, where the bowler is expected to use approximately 1.3 times the amount of side flexion that they obtained during a standing range of motion trial.[12] Lateral flexion may be inherently linked to effectiveness of the bowling action. The need for performance needs to be balanced with the need for injury prevention, as lateral flexion to the left has also been associated with injury.[13]

Here, shoulder position was assessed and described relative to the pelvis and care should be taken in the comparison of data with studies where shoulder girdle orientation was measured relative to the transverse plane.[2,3,12] Rotation of the shoulder girdle to the left in relation to the pelvis is a common component of the pace bowling action at front foot placement and was found to be associated with higher ball release speeds in this study (Table 1). Maximum pelvic to shoulder separation occurs 0.03s after front foot impact in injury free fast bowlers,[12] while a shoulder separation angle, where the shoulders are more rotated to the left in relation to the pelvic position slightly before front foot placement, has been associated with higher ball release speeds.[1] At front foot placement, bowlers may display a shoulder to hip separation angle where the shoulders are rotated to the left in preparation for the relative rotation to the right that will follow towards ball release. Bartlett et al[2] suggested that maximal shoulder counter-rotation stretches the prime muscles responsible for rotation of the trunk. It is thought that the stored elastic energy resulting from the stretch is used during the subsequent rotation.[2] Myers et al[14] found that an increase in stored energy results in an increase in power build up and will lead to a more forceful swing in golfers. By increasing the shoulder to hip separation angle, stretching (eccentric lengthening) of a particular muscle storing potential energy occurs in order to increase power output of the same muscle during the final phase of the movement (concentric shortening). Thus in order to create maximal force production, the stretch-shorten cycle uses a muscle's elastic and reactive properties, while stimulating joint proprioceptors and increase muscle recruitment.[15,16]

At the start of the cricket season (Table 1) there were clear correlations of multiple variables with higher ball release speeds, while at the end of the cricket season only two variables were correlated with ball release speeds. At the end of the cricket season only thorax to arm angle were again associated with higher ball release speeds, while none of the spinal variables were associated. At the start of the cricket season all bowlers were injury free which resulted in clear associations, while the incidence of injury, micro-trauma or overuse during the cricket season may have altered the bowling technique as a result of fear-avoidance[17] or pain-adaptation protective strategies[18] which may be the reason for the lack of correlations found at the end of the cricket season. Furthermore, it is also possible that not all variables are consistently associated with ball release speed as cross-sectional data suggest. Arm to thorax angle, the only variable that was associated with ball release speed at both the start and the end of the season, is a non-weight bearing component of the kinetic chain. Considering the known load that is placed on the low back during the pace bowling action, it is possible that injury, micro-trauma or overuse affected the low back and lower limbs rather than the upper limb via the kinetic chain.

A limitation of this study, although statistically significant (and in spite of a relatively large sample size), was that only fair to moderate relationships between kinematic variables and ball release speed were found. This may suggest that each of the kinematic variables implicated in this study only represent a minor contribution to higher ball release speeds. Furthermore, skin markers were used which introduces its own set of errors in estimating spinal movements due to skin movement. Future research in the influence of overuse, micro-trauma and injury on performance measures is needed. Also studies that investigate the effect of kinematic variables on accuracy should be considered.

5. Conclusion

Front knee, arm to thorax, global trunk flexion, rotation, lateral flexion as well as segmental (L1, T10 and T7) spinal lateral flexion angles were associated with ball release speed. Most statistically significant relationships were found at the start of the season. At the start of the cricket season all bowlers were injury free which resulted in clear associations, while the incidence of injury, micro-trauma or overuse during the cricket season may have altered the bowling technique as a result of fear-avoidance or pain-adaptation protective strategies. Bowling accuracy was associated with a more extended front knee angle, although no other kinematic variables showed an association. The reward of performance should be balanced by the penalty of injury as front knee angles as well as shoulder counter-rotation have previously been associated with injury in cricket pace bowlers.

6. Practical Implications

- The strong demand for high ball release speeds may motivate pace bowlers to incorporate certain technique-related intrinsic factors into the bowling action to increase ball release speed at the expense of injury prevention.
- A more extended front knee angle may play a role in the achievement of higher ball release speeds.
- If the arm is in a position more to the right of the trunk at front foot placement, more internal rotation until ball release is possible. More internal rotation is associated with higher flexion and extension elbow angles (throwing) and subsequently an increase in ball release speed.

7. Acknowledgements

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9. Supplementary material

Table 1
Description of regional spine and knee kinematic variables as calculated in the current study

Knee angle	A knee angle of 180˚ refers to a straight knee and a knee angle below 180˚ describes knee flexion.
Arm to thorax angle	Arm to thorax angle refers to the angle between a vector describing arm position (shoulder joint to ball) and a vector describing the thorax position (0 - arm is parallel to thorax; negative - arm is to the left of thorax; positive – arm is to the right of thorax).
Ball release height	Ball release height is the height of the ball relative to the ground plane at the time of ball release.
Sh-Pelv Flex/LF Rot	Shoulder girdle position in relation to pelvic position was defined as positive for flexion, lateral flexion to the left and rotation to the left. A XYZ (flexion, adduction, rotation) Cardan rotation sequence was used to calculate the relative movement of the pelvis and shoulder girdles, using independent established reference frames for the respective girdles. The relative motion of the shoulders to the pelvis was calculated as the difference in the specific rotation angle.
Sh-Pelv Flex/LF/Rot range between BR and FFP	Shoulder girdle position in relation to pelvic position range between ball release and front foot placement was calculated by subtracting the angle calculated at ball release from the angle calculated at front foot placement.
L1, T10, T7 LF	Lateral flexion refers to lateral flexion of L1/T10/T7 in relation to the pelvis (90˚indicates upright standing in neutral position; <90˚ indicates lateral flexion to the left; >90˚ indicates lateral flexion to the right). Lateral flexion angles were calculated as the angle between the pelvis plane (transverse plane, established by the limits of sacral and left and right anterior superior iliac spine markers) and the plane to the relevant markers along the sagittal plane (established by the limits of sacral, midpoint between the anterior superior iliac spines markers, and one of the markers on either L1, T10 or T7).
L1, T10, T7 Flex	Flexion refers to the planar flexion angle between the different segments namely L1 flexion (angle between T10, L1 and S1); T10 flexion (angle between T7, T10 and L1); T7 flexion (angle between C7, T7 and T10). A flexion/extension angle <180˚indicates spinal flexion; an angle >180˚ indicates spinal extension.
L1, T10, T7 LF/Flex range between BR and FFP	Lateral flexion or flexion range between ball release and front foot placement was calculated by subtracting the angle calculated at ball release from the angle calculated at front foot placement.

Table 2
The relationship between kinematic variables and ball release speed as measured at the start of the cricket season

Kinematic Variable	Correlation coefficient (r)	Number of bowlers (n)	p-value
Knee angle at FFP	0.404	27	0.037*
Knee angle at BR	0.026	22	0.910
Change in knee angle between FFP and BR	0.025	22	0.912
Arm to thorax angle at FFP	0.504	31	0.004*
Arm to thorax angle at BR	0.274	20	0.242
Ball release height	0.190	24	0.374
Sh-Pelv Flex at FFP	0.121	31	0.516
Sh-Pelv Flex at BR	-0.367	30	0.046*
Sh-Pelv Flex range between BR and FFP	-0.398	30	0.029*
Sh-Pelv LF at FFP	0.362	31	0.045*
Sh-Pelv LF at BR	0.464	30	0.010*
Sh-Pelv LF range between BR and FFP	-0.033	30	0.861
Sh-Pelv Rot at FFP	0.411	31	0.022*
Sh-Pelv Rot at BR	-0.322	30	0.082
Sh-Pelv Rot range between BR and FFP	-0.276	30	0.139
L1 LF at FFP	-0.450	31	0.011*
L1 LF at BR	0.362	29	0.054
L1 LF range between BR and FFP	-0.218	30	0.247
T10 LF at FFP	-0.466	31	0.008*
T10 LF at BR	0.334	30	0.071
T10 LF range between BR and FFP	-0.161	30	0.396
T7 LF at FFP	-0.509	31	0.003*
T7 LF at BR	0.324	30	0.081
T7 LF range between BR and FFP	-0.104	30	0.586
L1 Flex at FFP	-0.099	31	0.595
L1 Flex at BR	-0.280	29	0.141
L1 Flex range between BR and FFP	0.100	30	0.601
T10 Flex at FFP	-0.015	31	0.938
T10 Flex at BR	-0.148	29	0.444
T10 Flex range between BR and FFP	0.058	30	0.762
T7 Flex at FFP	0.013	31	0.945
T7 Flex at BR	-0.084	30	0.658
T7 Flex range between BR and FFP	0.040	30	0.835

Arm to thorax angle refers to the angle of the arm (shoulder joint to ball) relative to the thorax (0- arm is parallel to thorax; negative arm is more to the left of thorax; positive are to the right of thorax)
Sh-Pelv Flex refers to shoulder girdle flexion in relation to the pelvis- positive value indicates flexion
Sh-Pelv LF refers to shoulder girdle lateral flexion in relation to the pelvis- positive value indicates lateral flexion to the left
Sh-Pelv Rot refers to shoulder girdle rotation in relation to the pelvis- positive value indicates rotation to the left
LF refers to lateral flexion of L1/T10/T7 in relation to the pelvis (90˚-upright standing, neutral position; <90˚-lateral flexion to the left; >90˚-lateral flexion to the right)
Flex refers to a flexion angle between the different segments namely L1 Flex (angle between T10, L1 and S1); T10 Flex (angle between T7, T10 and L1); T7 flexion (angle between C7, T7 and T10); angle <180˚-spinal flexion; angle >180˚-spinal extension
BR-ball release; FFP-front foot placement
* indicates statistical significance ($p<0.05$)

Table 3
The relationship between kinematic variables and ball release speed as measured at the end of the season

Kinematic Variable	Correlation coefficient (r)	Number of bowlers (n)	p-value
Knee angle at FFP	-0.198	26	0.331
Knee angle at BR	0.307	23	0.154
Change in knee angle between FFP and BR	-0.457	23	0.028*
Arm to thorax angle at FFP	0. 448	29	0.015*
Arm to thorax angle at BR	0.400	22	0.065
Ball release height	0.087	25	0.678
Sh-Pelv Flex at FFP	0.045	28	0.819
Sh-Pelv Flex at BR	0.321	27	0.102
Sh-Pelv Flex range between BR and FFP	0.064	28	0.745
Sh-Pelv LF at FFP	-0.137	28	0.487
Sh-Pelv LF at BR	0.119	27	0.555
Sh-Pelv LF range between BR and FFP	0.147	28	0.457
Sh-Pelv Rot at FFP	0.069	28	0.728
Sh-Pelv Rot at BR	-0.366	27	0.060
Sh-Pelv Rot range between BR and FFP	-0.241	28	0.217
L1 LF at FFP	-0.344	28	0.073
L1 LF at BR	0.153	27	0.446
L1 LF range between BR and FFP	0.063	27	0.754
T10 LF at FFP	-0.335	28	0.081
T10 LF at BR	0.113	28	0.567
T10 LF range between BR and FFP	0.034	28	0.864
T7 LF at FFP	-0.320	28	0.096
T7 LF at BR	0.154	27	0.442
T7 LF range between BR and FFP	0.095	27	0.636
L1 Flex at FFP	0.151	28	0.444
L1 Flex at BR	-0.083	27	0.680
L1 Flex range between BR and FFP	-0.111	27	0.581
T10 Flex at FFP	0.169	28	0.390
T10 Flex at BR	0.245	27	0.217
T10 Flex range between BR and FFP	-0.365	27	0.061
T7 Flex at FFP	-0.166	28	0.398
T7 Flex at BR	0.091	27	0.651
T7 Flex range between BR and FFP	-0.073	27	0.719

Arm to thorax angle refers to the angle of the arm (shoulder joint to ball) relative to the thorax (0- arm is parallel to thorax; negative arm is more to the left of thorax; positive are to the right of thorax)
Sh-Pelv Flex refers to shoulder girdle flexion in relation to the pelvis- positive value indicates flexion
Sh-Pelv LF refers to shoulder girdle lateral flexion in relation to the pelvis- positive value indicates lateral flexion to the left
Sh-Pelv Rot refers to shoulder girdle rotation in relation to the pelvis- positive value indicates rotation to the left
LF refers to lateral flexion of L1/T10/T7 in relation to the pelvis (90˚-upright standing, neutral position; <90˚-lateral flexion to the left; >90˚-lateral flexion to the right)
Flex refers to a flexion angle between the different segments namely L1 Flex (angle between T10, L1 and S1); T10 Flex (angle between T7, T10 and L1); T7 flexion (angle between C7, T7 and T10); angle <180˚-spinal flexion; angle >180˚-spinal extension
BR-ball release; FFP-front foot placement
* indicates statistical significance ($p<0.05$)

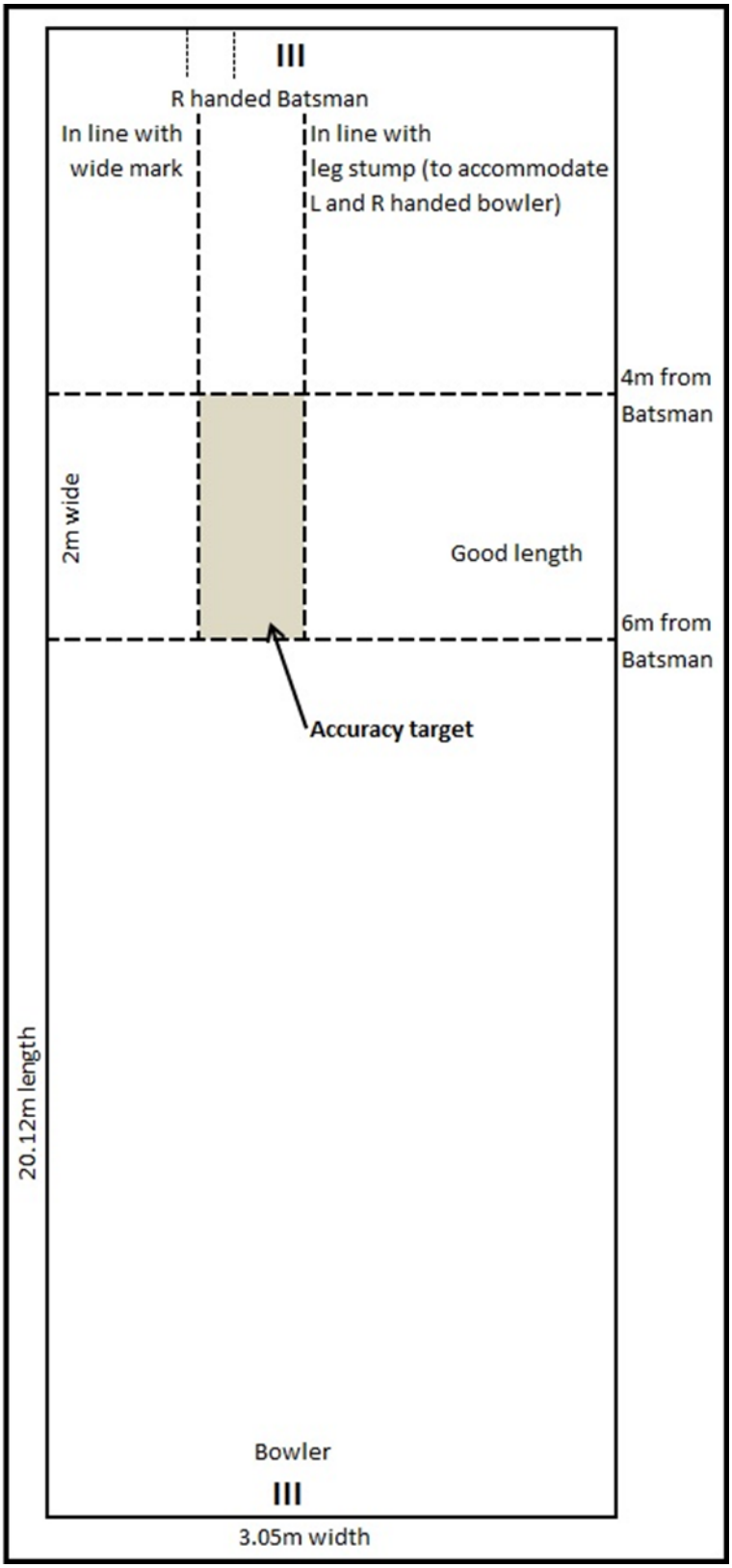

Figure 3 – A schematic presentation of the bowling accuracy target set up at good length on the pitch.

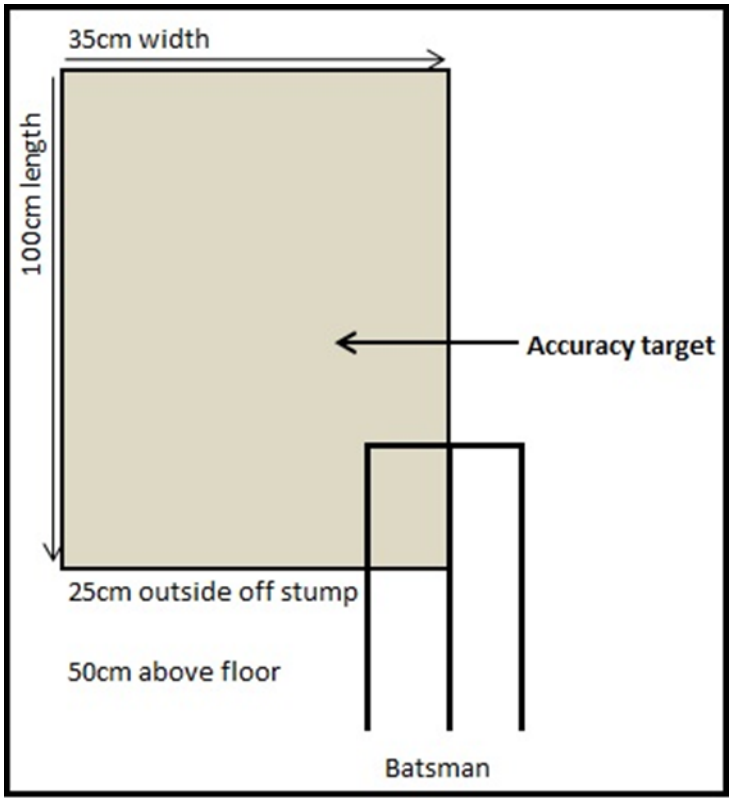

Figure 4 – A schematic presentation of the bowling accuracy target set up behind the stumps.

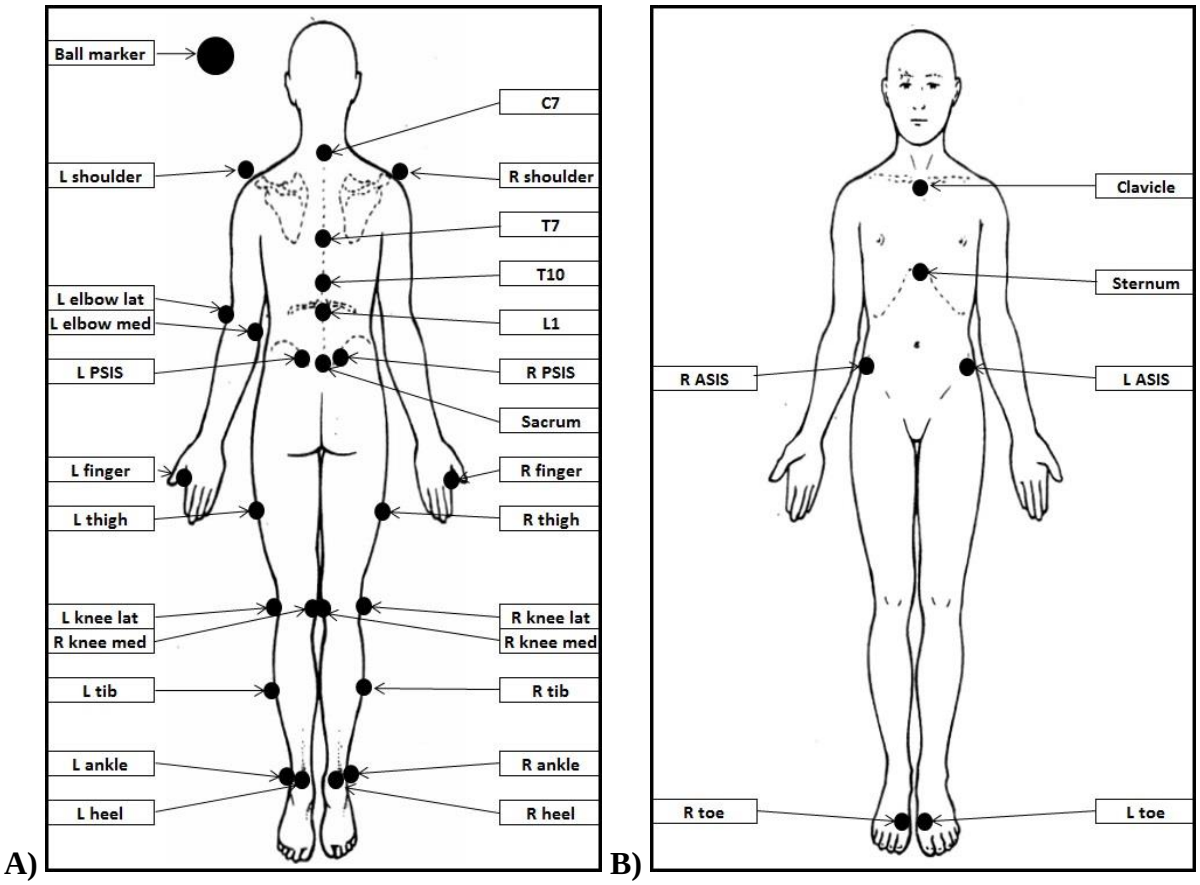

Figure 5 – Light reflective marker placement: A) Posterior view; B) Anterior view.

2. Linking Notes between Chapters 4 and 5

This section contains information to clarify the link between Chapters 4 and 5. In depth discussions in findings of individual papers are in the discussion sections of each paper, while an overall discussion follows in Chapter 8.

In both Chapters 4 and 5, kinematic variables (spinal and knee angles), which can also be described as technique-related intrinsic factors, that occur during the pace bowling action are associated with injury and performance, respectively. In these two chapters, some of these technique-related intrinsic factors were found that were simultaneously associated with both increased injury and with increased performance. One example is the knee angle during the power phase of the pace bowling action. A more extended knee is associated with higher ball release speed, while a more flexed knee is associated with a decrease in injury incidence.

CHAPTER 6 – Paper 5: Olivier B, Stewart AV, Green AC and McKinon W (2013) Knee Joint Position Sense does not Correlate with Front Knee Angles or Ball Release Speed in Cricket Pace Bowlers, *Gazzetta Medica Italiana* (in press)

This paper was accepted for publication in the *Gazetta Medica Italiana*, it was however not yet published by the time that this thesis was due for submission. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article, although general formatting is aligned with the requirements of the specific journal.

1. Original Paper

Title: Knee Joint Position Sense does not Correlate with Front Knee Angles or Ball Release Speed in Cricket Pace Bowlers

Authors: Benita Olivier, Aimee Stewart, Andrew Green, Warrick McKinon

Abstract
Aim: The aim of this study was to establish if knee joint position sense in functional and pre-defined angles, are related to ball release speed.
Methods: Twenty one healthy male cricket pace bowlers participated in this study. The ability of each bowler to reproduce pre-defined knee angles of 140° and 160° of knee extension was assessed. In addition, in a subsample of 11 bowlers, elecrogoniometery was used to determine the angles of the knee at front foot placement and at ball release. Electrogoniometery was also used to assess the ability of this subsample of subjects to reproduce these bowling specific knee angles. Pearson's correlation coefficient was used to determine the relationship joint reposition error in these four positions and ball release speed (significance $p<0.05$).
Results: There was no statistically significant relationship between knee joint reposition error in the pre-defined (n=21) or bowling specific (n=11) knee angles and ball release speed. The ability of bowlers to reposition their knee angles were also not related to the measured knee angles at ball release or front foot placement.
Conclusion: It is likely that static knee joint position sense is not a major predictor of the dynamic knee angle during the bowling action, or of ball release speed in a homogenous group of competitive bowlers. Although other mechanisms, which are known to operate dynamically, may contribute to knee angles and bowling speeds, it is possible that leg specific proprioception does not play a major role in determining knee angles and bowling speeds.

KEY WORDS: proprioception, joint position sense, knee joint, cricket, fast bowler, pace bowler

Introduction

One key member of a cricket team is the pace bowler. The faster a bowler deliver the ball the more difficult it becomes for the batsman to play any shots due to a reduced reaction time. One of the factors that is known to influence bowling speed is the front knee angle at front foot placement and ball release positions during the bowling action.[1,2,3]

The greater the knee extension at front foot placement and ball release phases of bowling, the higher the ball release speed. Loram et al[3] and Portus et al[2] established that a front knee angle at front foot placement of approximately 160˚ to 164º and at a ball release position 148˚ to 150º of knee extension are more closely related to higher ball release speed than smaller knee angles. The reason why a relatively extended knee is associated with a higher ball release speed is thought to be due to an increased height at ball release[3] and due to more efficient transfer of kinetic energy to the ball.[2]

The ability to position the knee at a specific angle is dependent upon proprioception. Proprioception is defined as the sensation of joint movement (kinaesthesia) and joint position.[4,5] Joint position sense (a component of proprioception) is the ability to determine where a particular body part is in space. Proprioception, including joint position sense, is crucial for skill-demanding activities.[6,7] Joint position sense is able to distinguish elite from novice athletes in tennis players[6] free flyers[7] and gymnasts.[8] If the knee angle is important in increasing bowling speed, then the ability of the elite bowler to position the knee in the desired, optimal position (joint position sense) may be a contributing factor in increasing performance (ball release speed).

Should an enhanced joint positioning sense (proprioception) contribute to greater ball release speeds, proprioception focused training could be incorporated into training programmes with the aim of improving performance. Therefore the aim of this study was to establish if knee joint position sense in pre-defined angles of 140˚ and 160˚ of knee extension as well as functional, reproduced, closed-chain positions of front foot placement and ball release, are correlated to release speed.

Materials and Methods

Participants

Twenty one premier league cricket pace bowlers participated in this study. Bowlers were male, between 18 and 26 years of age and injury free at the time of testing. All bowlers had four or more years of pace bowling experience. Ethical clearance was obtained from the Human Research Ethics Committee of the associated tertiary institution.

Procedures

Bowlers first warmed-up in their own accustomed manner. Participants bowled six match pace deliveries aimed at a right hand batsman. A hand held radar gun (Stalker ATS®, Texas, USA) was used to capture ball release speed and was positioned 180º behind the ball release position.[9] Joint position sense in pre-defined angles of 140˚ and 160˚ of knee extension was measured in 21 bowlers. After being in the specific position for ten seconds, the bowler was removed from the position for ten seconds. The bowler was then asked to reposition his knee in the same position. Goniometer angles were recorded and error from initial position was calculated, to establish joint reposition error.

In a sub-sample of 11 bowlers, an electrogoniometer (Zebris®, Germany, Europe) was attached to the left knee in a right handed bowler and to the right knee in a left handed bowler. The two poles of the electrogoniometer were attached to the lateral surface of the knee, one on the distal part of the femur and the other on the proximal part of the tibia. The Bluetooth telemetry system (Zebris®) was strapped around the waist of the bowler in a position that did not hinder movement during the bowling action. Electrogoniometry were logged using MyoResearch® (Scottsdale, Arizona) software. The electrogoniometer was calibrated each time before it was used. The electrogoniometer values at these angles were used to reposition the participant's knees after the bowling action in exactly the same position they were in during the front foot placement and ball release instances of the bowling action. Bowlers were in a weight bearing position. Joint position sense was measured and reposition error was calculated as described above.

Sagittal plane video data was captured using a high speed digital camera (PixeLINK® PL-A741, Ottawa, Ontario) which recorded at 85 frames per second. Front foot placement was defined as the first frame when the front (non-dominant) toe marker reached its lowest position; ball release was defined as the first frame observed where the ball was no longer in contact with the bowler's hand.[9] Ball release speed, high speed video recording and electrogoniometric measurements were obtained simultaneously during the same bowling action.

Data analysis

Knee joint reposition error was calculated for 21 bowlers in the positions of 140˚ and 160˚ knee extension and for 11 bowlers in the front foot placement and ball release positions as well. Pearson's correlation coefficient was calculated between knee joint reposition error in four static reproduced positions (front foot placement, ball release, 140˚ and 160˚ knee extension), kinematic knee joint angles at front foot placement and ball release, and ball release speed.

Results

The mean ball release speed was 124.09 km/hr (standard deviation ±7.47 km/hr).

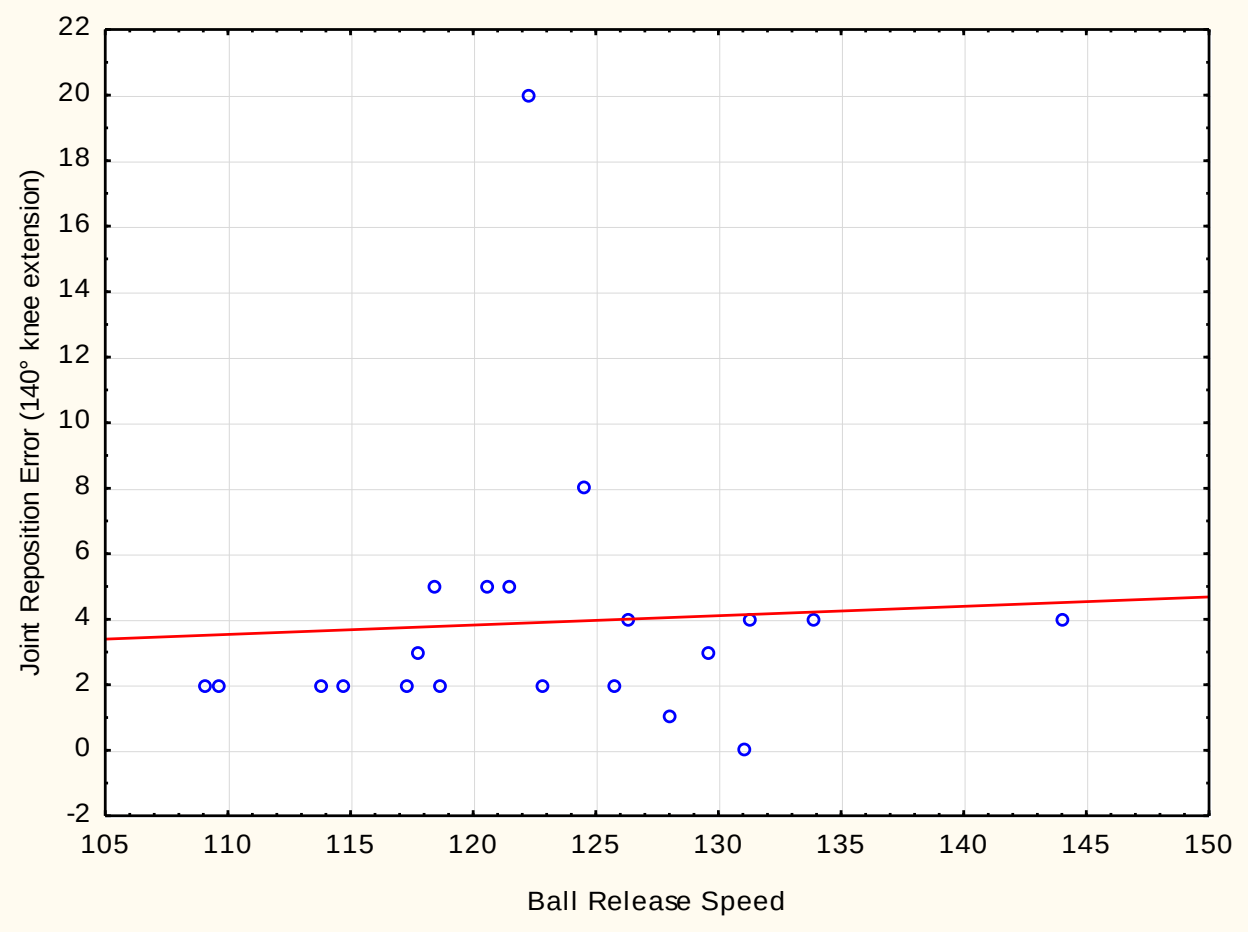

FIGURE 1 - *The correlation between joint reposition error in the position of 140˚ knee extension and ball release speed (r=0.06) (n=21).*

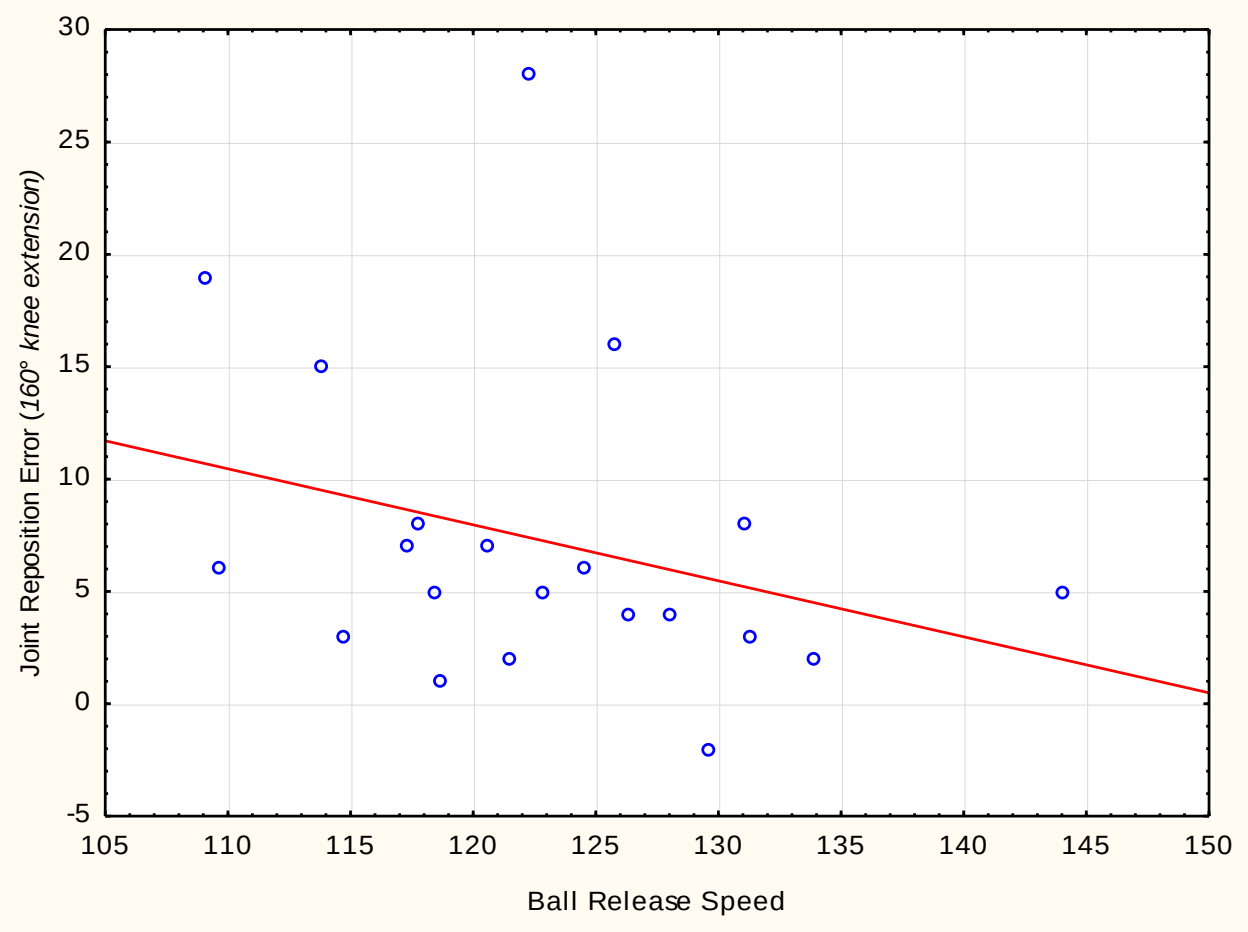

FIGURE 2 - *The correlation between joint reposition error in the position of 160˚ knee extension and ball release speed (r=-0.30) (n=21).*

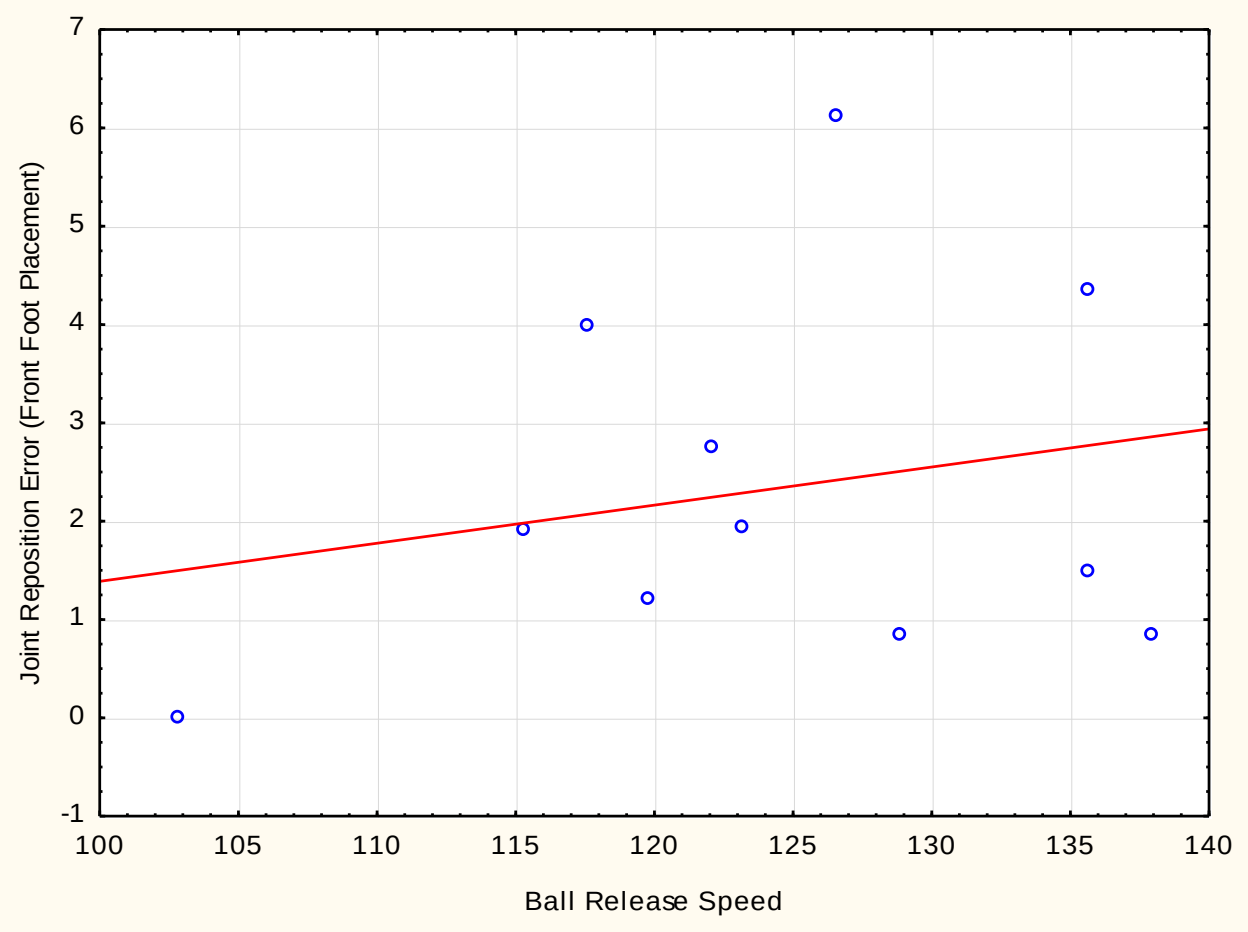

FIGURE 3 - *The correlation between joint reposition error in the front foot placement position and ball release speed (r=0.22) (n=11).*

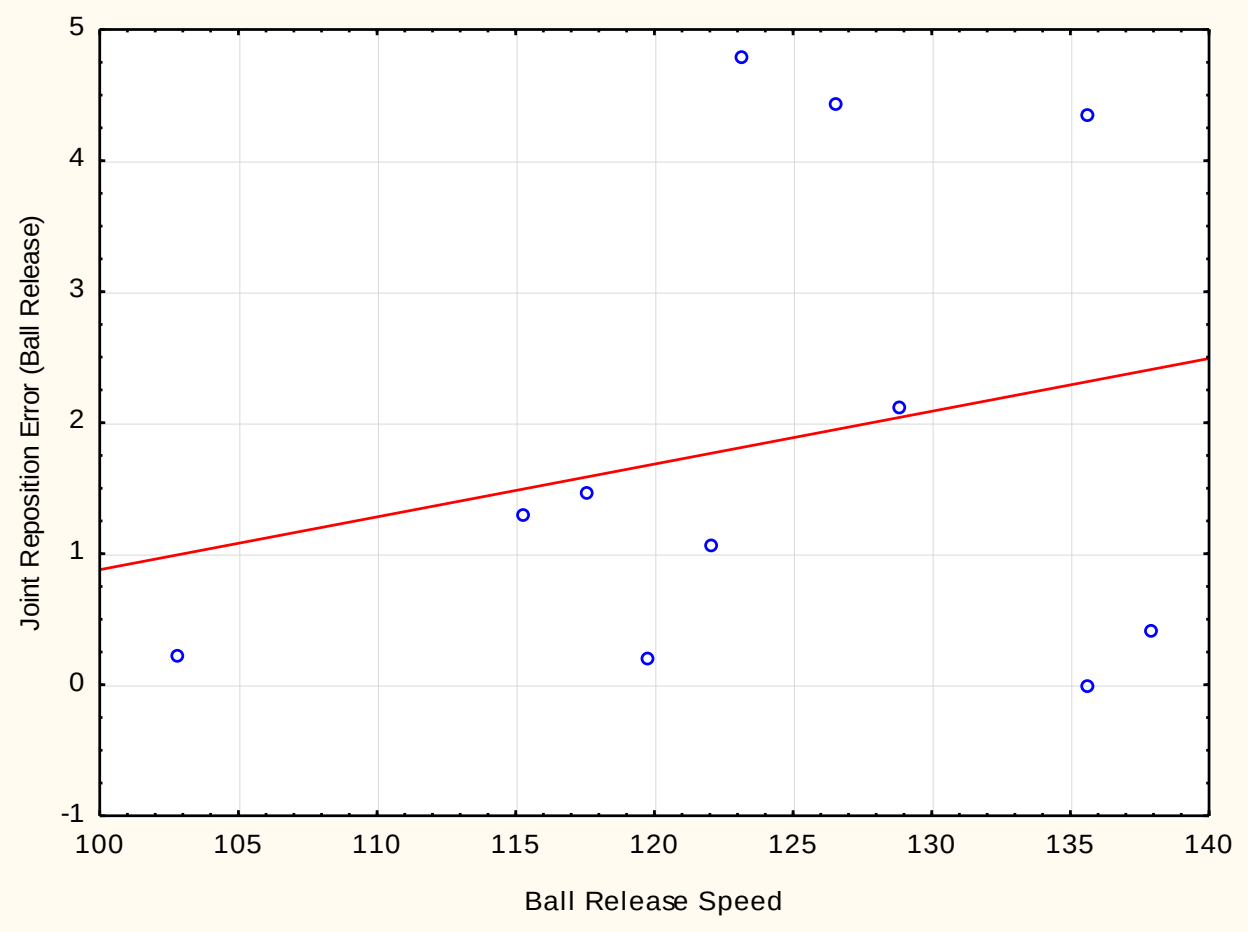

FIGURE 4 - *The correlation between joint reposition error in the ball release position and ball release speed (r=0.23) (n=11).*

There was no statistically significant relationship between knee joint reposition error as measured in reproduced, static positions and ball release speed (Figures 1-4).

TABLE 1. - *The correlation between knee position error and knee angles during the bowling action (n=11).*

Reproduced position	**Front foot placement knee angle Correlation Coefficient (r-value)**	**Ball release knee angle Correlation Coefficient (r-value)**
Front foot placement	-0.08	0.09
Ball release	-0.20	-0.19
140˚ knee extension	-0.05	0.19
160˚ knee extension	-0.35	-0.04

Knee joint reposition error measured in reproduced, static positions and kinematic knee angles did not show any statistically significant correlations as depicted in Table 1 (significance $p<0.05$).

Discussion

No correlation between knee joint reposition error in static, reproduced (140˚ and 160˚ of knee extension), as well as functional, bowling specific (front foot placement and ball release) positions and ball release speed was found in this study (Figures 1-4). Our data therefore suggests that knee joint position sense measured statically is not correlated with ball release speed in competitive pace bowlers such as those in this study.

The lack of a significant correlation between joint reposition sense (in general) and ball release speed is different to what has been found for other sports where similar measurements of proprioception are linked to performance.[8,6,7] In addition knee position error did not correlate to actual bowling knee angles at front foot placement and ball release (Table 1), showing that the ability of a bowler to reposition his knee into a predetermined static position did not relate to the angle of his knee during the bowling action. When these measurements were repeated at participant and delivery specific functional knee angles (the front foot placement and ball release positions), joint position sense again did not correlate to the actual knee angles or to ball release speed. In the latter half of the study, the exact, functional angle was chosen to replicate the different degrees of knee flexion which lead to different amounts of tension in muscles, capsules and ligaments during the bowling action.[10] Additionally, bowlers were tested in a weight bearing position to replicate the functional requirements of the bowling positions as much as possible. We believe the weight bearing nature of such measurements were important because the function of the proprioceptors, including Ruffini's endings, Pacinian corpuscles, Golgi-Mazzoni corpuscles, Golgi tendon organs and muscle spindles, are enhanced by weight bearing positions, thus increasing the ability of joint position sense.[11,6]

It is possible that the static nature and voluntary mode of movement used by participants also played a role in the results found in this study. During the bowling action, specifically in the front foot placement and ball release phases, the knee joint is positioned for a few milliseconds at a specific angle. It is likely that static knee position sense does not relate to the dynamic angle that the knee is placed in during the bowling action. This may be because different neurophysiological pathways are used in an "unconscious", dynamic situation, to what is used when the knee is statically positioned into a predetermined position. Neurophysiological pathways for conscious sensory appreciation is associated with the dorsal lateral tracts while the spinocerebellar tracts are responsible for unconscious proprioception.[12]

Proprioception includes both neuromuscular and somatosensory components.[13] The somatosensory senses include conscious appreciations of propriopception, including kinaesthesia, joint position sense and sense of resistance.[12] Unconscious (involuntary) control in proprioception is reflected in neuromuscular senses, including posture control, joint stability and muscle reaction times. Proprioception i.e. awareness of limb position, joint angles, and muscle tension and length are used in reflexive, automatic and voluntary reactions that are part of the bowling action. Friden et al[10] suggests that proprioception during slow velocities maximally stimulates joint receptors, while active reproduction tests stimulate both muscle and joint receptors. Ruffini receptors behave as both static and dynamic receptors, while the Pacinian corpuscles are classified as dynamic receptors.[12] During the bowling action muscle activations take place unconsciously and synonymously take into account requirements of the task, i.e. speed and load. Unconscious proprioceptive input with regards to the angle of the knee joint and surrounding structures is essential for neuromuscular control during the bowling action.[12]

It is clear that conscious proprioception was tested in this study, while the demands of the bowling action relate to proprioception on an unconscious, automatic level. Joint position sense has been tested in non-functional, static positions in dancers,[13] tennis players,[6] anterior cruciate ligament reconstruction patients,[5] healthy individuals,[10] free flyers[7] and gymnasts.[8] However from the results of this study it is possible that the assessment of proprioception requires replications of the high speeds at an automated level, and not merely testing that is done in a static position where the demands of the sport are not optimally replicated [14].

Considerations should be given to other factors that may play a role in determining a bowler's knee angle and subsequently influenced the results in this study. Individual anatomical variations in knee range of motion and mobility of ligaments, muscles and tendons are likely to be present. These variations can influence the knee position that a bowler favours during the bowling action. Additionally, proprioceptors in and around the knee joint may be developed or functioning at different levels. Individual variety may include differences in the sensitivity of specific proprioceptors e.g. between muscle and joint receptors. Should joint receptors be functioning differently to muscle receptors, such variation may lead to a situation where a bowler will better be able to sense change in slow velocities than faster velocities.[10]

The ability of a bowler to consistently position his knee at an angle that facilitates a high ball release speed may be seen as a more relevant way to describe and rate proprioception in the pace bowler. This "automated" ability can be described as a form of proprioception or awareness of joint position in space. The assumption can be made that if a bowler is able to consistently position their knee at an optimal angle during the front foot placement and ball release bowling phases of pace bowling, then his proprioceptive awareness should be well defined in these two positions which are crucial for high ball release speed. Further research in testing proprioception at high speeds and at an automated level is warranted.

Conclusion

Data from the present study show that joint position sense in static arbitrary and even action specific joint positions do not correlate with performance in a similar way to what has been found for other sporting disciplines. Despite this, is it possible that a more dynamic form of proprioception may yet contribute to knee poisoning in cricket pace bowlers. Individual anatomical variety in mobility of ligaments, muscles and tendons, as well as functioning of the different proprioceptors should be taken into consideration. To this this end attention should be given to the exact proprioceptive role that is required during the specific requirements of the sport under review. Future studies may develop dynamic methods of assessing action specific proprioception, which may be able to better assess involuntary proprioception.

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2. Linking Notes between Chapters 5 and 6

This section contains information to clarify the link between Chapters 5 and 6. In depth discussions in findings of individual papers are in the discussion sections of each paper, while an overall discussion follows in Chapter 8.

Paper 4 investigated the kinematic variables associated with performance and found that a more extended front knee angle at front foot placement is associated with higher ball release speed. Paper 5 attempted to find an association between front knee angle as a kinematic variable, knee proprioception as an intrinsic factor and ball release speed as a performance variable. Both these papers thus investigate the link between intrinsic factors and performance, with Paper 4 investigating technique-related intrinsic factors and Paper 5 investigating an intrinsic factor that was hoped to optimise performance and at the same time decrease injury incidence rates.

CHAPTER 7 – Paper 6: Olivier B, Stewart AV and McKinon W (2013) Side to Side Asymmetry in Absolute and Relative Muscle Thickness of the Lateral Abdominal Wall in Cricket Pace Bowlers, *South African Journal of Sports Medicine,* 25(3): 81-86

At the time of this thesis submission, paper 1 was published in the *South African Journal of Sports Medicine,* as an original article. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article and general formatting is aligned with the requirements of the specific journal.

1. Original Paper

Title: Side to Side Asymmetry in Absolute and Relative Muscle Thickness of the Lateral Abdominal Wall in Cricket Pace Bowlers

Authors: Benita Olivier, Aimee V. Stewart, Warrick Mckinon

Abstract
Background: The abdominal musculature plays a protective role against low back injury. Knowledge of the asymmetry in abdominal wall thickness in healthy, injury free cricket pace bowlers may provide a useful platform against which pathology could be assessed and the effects of training could be evaluated.
Objective: The aim of this study was to compare the side to side differences in absolute muscle thickness and activity of the abdominal musculature as well as to compare absolute muscle thickness and muscle activity measured at the start to measurements at the end of a cricket season in a group of amateur pace bowlers.
Methods: This was a controlled longitudinal prospective study. Rehabilitative ultrasound imaging was used to assess abdominal muscle thickness in twenty six right handed injury free cricket pace bowlers at the start and at the end of a cricket season. Thickness measurements were done at rest, during an abdominal drawing in manoeuvre (ADIM) and the active straight leg raise (ASLR) on both the left (L) and right (R).
Results: The absolute thickness of the non-dominant obliquus abdominis internus (OI) was higher than that of the dominant OI at the start ($p<0.001$; ES=0.87) as well as at the end of the cricket season ($p<0.001$; ES 1.09). At the start of the season the percentage change during the ADIM, thus muscle activity, was higher for the non-dominant OI than for the dominant OI ($p=0.02$; ES=0.51). Absolute thickness of the dominant obliquus abdominis externus (OE) at rest was significantly higher at the end of the season compared to at the start of the season ($p<0.001$; ES=0.85). During ASLR R, the activity of the left transversus abdominis (TA) is significantly higher than that of the right TA during ASLR L ($p=0.03$) when measured at the end of the season.
Conclusion: This study highlights the possible muscle adaptations in absolute muscle thickness and activity as a consequence of the asymmetrical bowling action.

Key words: *abdominal muscles, cricket, pace bowler, fast bowler, rehabilitative ultrasound imaging*

Introduction

Low back injury is one of the most common types of injury sustained by cricket pace bowlers.[1,2,3,4,5] The abdominal musculature plays a protective role against low back injury by increasing the stability of the lumbar segmental vertebrae.[6,7,8] The assessment of thickness of the abdominal muscles including transversus abdominis (TA), obliquus abdominis internus (OI) and oblique abdominis externus (OE) is known to be a valid measure of size of the abdominal muscles, as well as a sensitive measure of change.[9] Hodges *et al.* (2003)[10] and Ferreira *et al.* (2011)[11] found that TA and OI percentage change in thickness is a valid measure of activity when compared to electromyography (EMG). Rehabilitative Ultrasound Imaging (RUSI) is often used as a surrogate measure for activation of the abdominal muscles. Muscle thickness as measured by RUSI is well correlated with muscle thickness measurements using Magnetic Resonance Imaging (MRI).[12]

Mannion *et al.*(2002)[13] and Springer *et al.*(2006)[14] conducted abdominal muscle activation studies in non-sporting populations and showed that there were no differences in activation between body sides. Rankin *et al.*(2006)[15] also found no statistically significant differences in muscle thickness between the left and right OI and OE when measured at rest, but a difference in TA was found where the left TA was thicker than the right in moderately active individuals. They did not specify whether the recreational activities were mainly symmetrical or asymmetrical. In contrast to the findings of Mannion *et al*.(2008),[13] Springer *et al*.(2006)[14] and Rankin *et al*. (2006),[15] Hides *et al*.(2008)[16] found that the OI on the non-dominant side of elite cricketers was thicker than on the dominant side. Hides *et al.'s* (2008)[16] study assessed a small sample size consisting of elite cricketers, including batsmen and bowlers. It was suggested that the asymmetrical demands of the repetitive bowling action may cause some muscles to be preferentially activated and hypertrophied above other muscles.[16]

Knowledge of the asymmetry in abdominal wall thickness in healthy and injury free cricket pace bowlers may provide a useful platform against which aetiology of injury could be assessed, training could be gauged and which could be used as a benchmark to direct RUSI biofeedback interventions in the future. Therefore the aim of this study was to compare the side to side differences in absolute muscle thickness and muscle activation of the abdominal musculature as well as to compare absolute muscle thickness and muscle activation measured at the start to measurements at the end of a cricket season in a group of amateur fast, fast-medium and medium pace bowlers.

Methods

Participants

Twenty six right handed premier league (amateur) cricket pace bowlers were invited to participate in the study on condition that they were free of injury. Participants were tested at the start and again at the end of an eight month cricket season. Ethical clearance was granted by the Human Research Ethics Committee of the associated tertiary institution. All participants gave written informed consent and had the right to withdraw from the study without suffering any repercussions.

Validity and Reliability

The criterion-related validity of RUSI to measure muscle thickness has been established against MRI.[12] A strong linear relationship is also known to exist between abdominal muscle thickness change (TA and OI) and EMG amplitude during low levels of muscle contraction (up to 30% of maximum voluntary contraction).[10,17] No consistent relationship was found between OE thickness change and muscle contraction, and should thus not be used to detect muscle activity.[10,11] Intra-rater reliability was established by Springer *et al*.(2006)[14] as being

between 0.93 (95% CI0.86-0.96) to 0.99 (95% CI0.98-1.00) as well as by Rankin *et al.*(2006)[15] as being 0.98 to 0.99 (95% CI 0.91-1.00).

Procedures

Abdominal muscle thickness was measured using a DP-6600 Digital ultrasonic imaging system® (Shenzhen Mindray Bio-medical Electronics Co., Ltd, China) with a 5MHz curvilinear transducer with a large footprint (≥60mm).[18] The first author underwent training in the use of the equipment and performed all the measurements. RUSI was done in brightness (B) mode. The ultrasound echo was recorded as a cross-sectional grey-scale image.[19]

Each participant was positioned in supine with their legs straight. The transducer was placed along the lateral abdominal wall along the mid-axillary line, midway between the inferior angle of the rib cage (lower border of the 11th costal cartilage) and the iliac crest in the transverse plane.[20,21,22,19] The medial edge of the TA muscle was positioned at the medial edge of the ultrasound image.[19,23] This is the most appropriate position as all three muscles are well represented and relatively flat and easy to measure on the image.[15] All images were taken on the left and the right with the participant at rest at the end of relaxed expiration with the glottis open to avoid bracing.[22,19,23] The participants were then instructed to perform the abdominal drawing in manoeuver (ADIM) by exhaling and gently drawing their lower abdomen towards the spine[24] using 20% of the maximal voluntary contraction.[10] The following standardised instructions were given to each participant: "take a relaxed breath in and out, hold the breath out, and then draw in your lower abdomen without moving your spine."[21] Participants had the opportunity to practice the ADIM five times before measurements were taken.[25] After performing the ADIM the bowler were instructed to relax their abdominal muscles completely. During the active straight leg raise (ASLR) bowler had to lift his leg 5cm from the plinth.[19,26] ASLR was performed on the left (L) and right (R). The transducer position was kept constant during all of the above.[19] The research assistant verified proper execution of the ADIM and ASLR and recorded the frame number of each image. Thickness of TA, OI and OE was measured in millimeter on each of the following images: at rest, ADIM, ASLR L and ASLR R. The distance between the superior and inferior hyperechoic muscle fascias of the TA, OI and OE was measured in the centre of the muscle belly by using a vertical straight line through the middle of the image. Measurements were conducted perpendicular to the muscle fascia.[21,24,26]

Data Analysis

Statistical analysis was conducted using Statistica® Version 10 (StatSoft Inc, Tulsa, USA). Thickness was reported as absolute muscle thickness at rest (TA, OI and OE) and thickness percentage change or muscle activity (TA and OI). Thickness percentage change was calculated as muscle thickness during activity as a ratio to muscle thickness at rest,[10] thus muscle thickness in contracted state minus muscle thickness at rest, divided by muscle thickness at rest times 100.[24,26] Absolute thickness as well as thickness change on the dominant and non-dominant sides were compared using the paired Student's t-test. The absolute thickness and thickness change as recorded at the start of the cricket season were compared to thickness measurements at the end of the cricket season by using the paired Student's t-test.[15] Statistical significance was set at $p<0.05$. Effect sizes were calculated using Cohen's *d* where effect sizes of 0.2, 0.5 and 0.8 were interpreted as small, medium and large, respectively.[27]

Results

Twenty six healthy, male, right handed, fast, fast-medium and medium pace bowlers between the ages of 18 and 26 years participated in this study (mean age 21.8years, SD 1.8years).

Most bowlers had more than six years' experience with the exception of two bowlers who each had five years' experience as a pace bowler.

The absolute thickness of the non-dominant OI at rest is higher than that of the dominant OI as shown in Table 1, with large effect sizes found for pre-season (ES=0.87) and post-season (ES=1.09) measurements ($p<0.001$). No side to side difference was found in absolute muscle thickness at rest for TA ($p=0.25$ and $p=0.10$) and OE ($p=0.33$ and $p=0.76$) at the start or at the end of the season. At the start of the season the percentage change during the ADIM, thus muscle activity, was higher for the non-dominant OI than for the dominant OI ($p=0.02$; ES=0.51). This was not the case when looking at post-season OI activation during ADIM ($p=0.37$).

Absolute thickness of the dominant OE at rest was significantly higher at the end of the season compared to at the start of the season ($p<0.001$; ES=0.85), while no difference was found in TA ($p=0.07$) and OI ($p=0.28$) thickness (Table 2). Furthermore, no difference was found in recruitment of the dominant and non-dominant TA and OI in ADIM ($p=0.07$ to 0.75), ASLR L ($p=0.07$ to 0.88) and ASLR R ($p=0.06$ to 0.67) activity positions at the start compared to the end of the cricket season.

During ASLR R, the activity of the left TA is significantly higher than that of the right TA during ASLR L ($p=0.03$) when measured at the end of the season (Fig. 1C). The same is true for TA during the ASLR L ($p=0.17$) at the start of the season (Fig. 1A). During ipsilateral muscle activity in ASLR L and ASLR R the activation of the left TA is higher than that of the right TA (pre-season $p=0.79$ and post-season $p=0.15$).

Table 1. Absolute thickness at rest and percentage change* in thickness in ADIM, ASLR L and ASLR R activity positions of the dominant compared to the non-dominant TA, OI and OE†

	Pre-season (n=26)				Post-season (n=24)			
	Non-dominant Mean (SD)	**Dominant Mean (SD)**	**p-value**	**Effect size Cohen's *d***	**Non-dominant Mean (SD)**	**Dominant Mean (SD)**	**p-value**	**Effect size Cohen's *d***
TA								
Rest (mm)	4.6 (1.4)	4.9 (1.4)	0.25	0.17	4.9 (1.4)	5.3 (1.4)	0.10	0.35
ADIM % change	56.5 (47.7)	41.9 (31.2)	0.09	0.37	41.6 (34.8)	27.0 (27.1)	0.19	0.48
ASLR L % change	17.4 (34.2)	14.1 (30.8)	0.66	0.10	15.8 (25.6)	5.7 (21.9)	0.16	0.44
ASLR R % change	25.4 (35.5)	16.5 (26.3)	0.22	0.29	20.2 (35.2)	5.5 (20.8)	0.05	0.52
OI								
Rest (mm)	14.2 (4.1)	11.4 (2.4)	0.00†	0.87	15.2 (3.4)	11.9 (2.7)	0.00†	1.09
ADIM % change	13.0 (20.2)	2.7 (21.6)	0.02†	0.51	11.1 (15.5)	7.6 (13.5)	0.37	0.24
ASLR L % change	9.8 (27.7)	1.5 (20.1)	0.19	0.35	14.1 (19.3)	7.7 (21.5)	0.14	0.32
ASLR R % change	8.6 (21.4)	5.7 (20.6)	0.58	0.14	4.0 (24.0)	8.9 (19.8)	0.40	0.23
OE								
Rest (mm)	6.4 (2.3)	6.0 (1.4)	0.33	0.25	7.4 (2.6)	7.5 (2.1)	0.76	0.05

TA, Transversus Abdominis; OI, Oblique Abdominis Internus; OE, Oblique Abdominis Externus; ADIM, Abdominal Drawing-in Manoeuvre; ASLR L, Active Straight Leg Raise Left; ASLR R, Active Straight Leg Raise Right.

*Percentage change was calculated as a percentage of muscle thickness at rest = (muscle activated - muscle at rest) / muscle at rest x 100.

† Significant difference between dominant and non-dominant sides ($p<0.05$).

Table 2. Absolute thickness at rest and percentage change* in thickness in ADIM, ASLR L and ASLR R activity positions of TA, OI and OE at the start compared to the end of a cricket season (n=24)†

	Non-dominant				Dominant			
	Pre-season Mean (SD)	**Post-season Mean (SD)**	**p-value**	**Effect size Cohen's *d***	**Pre-season Mean (SD)**	**Post-season Mean (SD)**	**p-value**	**Effect size Cohen's *d***
TA								
Rest (mm)	4.6 (1.1)	4.9 (1.4)	0.13	0.22	4.9 (1.3)	5.3 (1.4)	0.07	0.38
ADIM % change	55.8 (46.2)	41.6 (34.8)	0.13	0.35	41.7 (32.3)	27.0 (27.1)	0.07	0.51
ASLR L % change	17.0 (35.4)	15.8 (26.6)	0.88	0.04	13.1 (31.7)	5.7 (21.9)	0.35	0.28
ASLR R % change	23.8 (34.8)	20.2 (35.2)	0.67	0.11	16.7 (27.3)	5.5 (20.8)	0.06	0.47
OI								
Rest (mm)	14.1 (3.9)	15.2 (3.4)	0.12	0.32	11.3 (2.3)	11.9 (2.7)	0.28	0.24
ADIM % change	12.6 (20.4)	11.1 (15.5)	0.75	0.08	2.0 (22.1)	7.6 (13.5)	0.25	0.31
ASLR L % change	9.7 (28.34)	14.1 (19.3)	0.48	0.19	0.03 (20.2)	7.7 (21.5)	0.07	0.38
ASLR R % change	8.7 (20.7)	4.0 (24.0)	0.45	0.21	4.7 (18.6)	8.9 (19.8)	0.41	0.22
OE								
Rest (mm)	6.5 (2.3)	7.4 (2.6)	0.12	0.35	6.0 (1.4)	7.5 (2.1)	<0.001†	0.85

TA, Transversus Abdominis; OI, Oblique Abdominis Internus; OE, Oblique Abdominis Externus; ADIM, Abdominal Drawing in Manoeuvre; ASLR L, Active Straight Leg Raise Left; ASLR R, Active Straight Leg Raise Right.

*Percentage change was calculated as a percentage of muscle thickness at rest = (muscle activated - muscle at rest) / muscle at rest x 100.

† Significant differences between pre- and post-season ($p<0.05$).

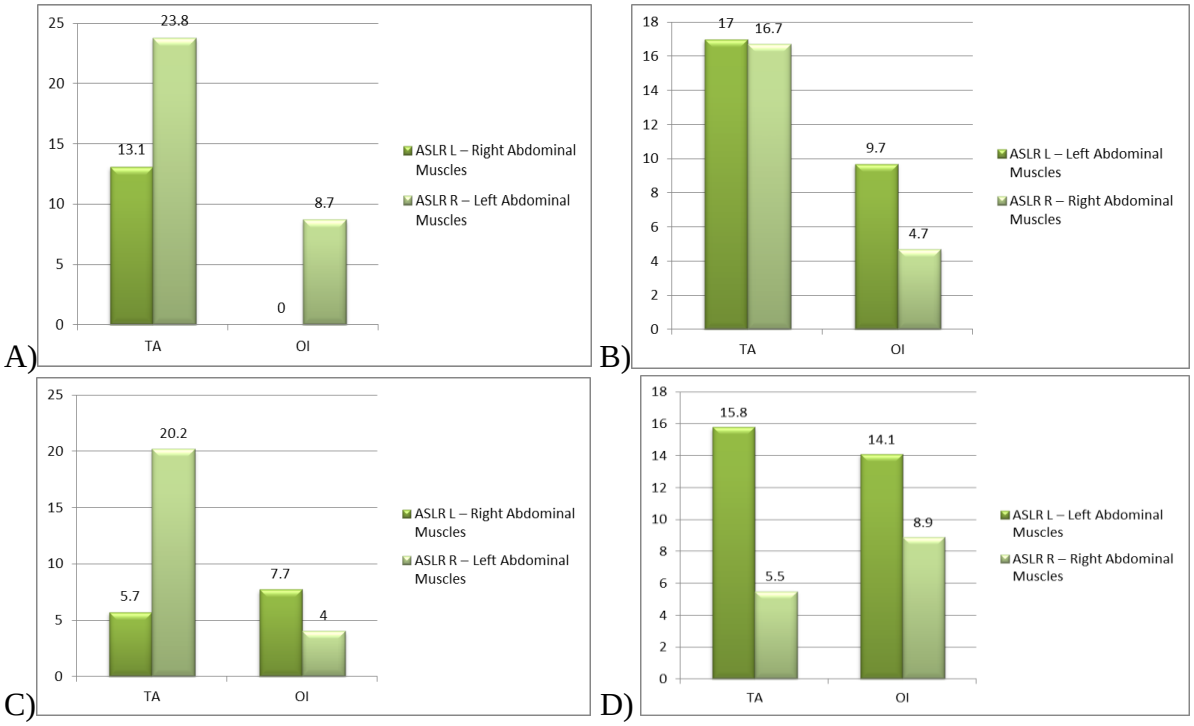

Fig. 1. Percentage change in thickness as measured A) pre-season, contra-lateral muscles (TA p=0.17; OI p=0.13); B) pre-season, ipsilateral muscles (TA p=0.79; OI p=0.48); C) post-season, contra-lateral muscles (TA p=0.03; OI p=0.50); D) post-season, ipsilateral muscles (TA p=0.15; OI p=0.31) during the ASLR L and ASLR R activity positions

Discussion

This study investigated the absolute thickness of TA, OI and OE at rest as well as TA and OI activity in ADIM, ASLR L and ASLR R activity positions, comparing body sides of healthy pace bowlers both at the start and at the end of a cricket season. In this study OI was the thickest muscle and TA the thinnest muscle which is similar to a study done by Mannion *et al*.(2008)[13] and Rankin *et al*.(2006).[15] The absolute muscle thickness of TA (4.6cm to 5.3cm) is slightly greater than that found by Mannion *et al.*(2008) (3.9cm to 4.0cm),[13] while the OI values (11.3cm to 15.2cm) in the present study are much higher and the OE values (6.0cm to 7.5cm) correspond closely to what was found by Mannion *et al*.(2008) (OI 8.3cm to 8.6cm; OE 6.7cm to7.1cm).[13] Mannion *et al*.(2008)[13] used a non-sporting population consisting of volunteers and this may explain their participants lesser TA and OI thickness values. In contrast, Rankin *et al*.(2006)[15] found a mean TA thickness (4.5cm to 5.1cm) similar to what was found in the present study, with thinner OI (11.7cm to 11.8cm) and thicker OE muscles (9.6cm to 9.7cm) in moderately active volunteers.[15] Although Hides and colleagues (2008)[16] did not measure OE thickness, they found higher thickness values for both TA (6.8cm to 7.2cm) and OI (16.7cm to 16.8cm) than in this study. The professional fast bowlers assessed in the latter study, were likely to be able to devote more time to pace bowling training and conditioning,[28] which may lead to greater hypertrophy of the abdominal musculature compared to less elite players. These differences in OI absolute thickness suggests that the more active the population, the larger the OI values and might indicate the particular activation of OI muscle during high load, repeated, asymmetrical physical activity. A similar trend was found in resting thickness for TA, but not for OE. It would appear that as the OI gets thicker the OE gets thinner, thus the relative balance in resting muscle thickness changes

as the activity of the individual changes. This hypothesis requires further study, however the consistent methods[29] used by the latter studies[15,16,13] may suggest that different abdominal muscles display far more complex responses to training than what was previously thought.

In the current study the absolute thickness of the OI at rest was significantly higher on the non-dominant side than on the dominant side both at the start as well as at the end of the cricket season as shown in Table 1. The large effect sizes emphasise the significance of this finding. In contrast to the findings in our study, Mannion *et al*.(2008)[13] and Springer *et al*.(2006)[14] found no statistically significant differences between the left and right abdominal muscle thickness and Rankin *et al*.(2006)[15] found asymmetries in TA thickness only. In Springer *et al.'s*(2006)[14] and Mannion *et al.*'s(2008)[13] case, they used a sample where no or few participants engaged in unilateral or rotational sporting activities. Springer *et al*.(2006)[14] suggest that individuals who routinely participate in rotational activities such as tennis and golf may be more likely to display asymmetries. Asymmetrical findings may increase the risk of developing pathology.[30,31] However, in a mathematical model used to estimate lumbar spinal stresses during quadratus lumborum muscle asymmetry, it was suggested that quadratus lumborum muscle asymmetry only causes small stresses and that it may even help reduce stress on the lumbar spine.[32] Participants in this study were all healthy, pain and injury free at the time of testing, which may suggest that factors other than pathology are responsible for the asymmetries found, as suggested by De Visser *et al*.(2007).[32] These differences in absolute muscle thickness on the non-dominant and dominant sides may be as a result of long term preferential use of the right bowling arm and subsequent preferential, asymmetrical recruitment of abdominal muscle fibres which may play a role in protection of the lumbar spine. It should however be noted that the asymmetries seen in pace bowlers are one of the factors predisposing them to their known susceptibility to lower back injury[1,2,3,31,33] but this asymmetry may also play a protective role.[32,34]

Taking into account the biomechanics of the pace bowling action, weight is put onto the non-dominant leg at front foot placement when the ground reaction force is extremely high,[35,36] which may mean that the ipsilateral OI has to contract to assist in absorbing the ground reaction forces taking into account the position that the pace bowler is in. In the present study the absolute thickness of the non-dominant OI was greater than that of the dominant OI which fits with the above theory. Also, while the non-dominant leg takes a vast amount of the load during the delivery stride, the dominant OE contracts in order to stabilise the pelvis in its typical cross over activation fashion.[37,38] The repetitive nature of a pace bowler's role in cricket training and in competition, resulting in many replicates of the bowling action may explain the greater OE absolute thickness values found in this study at the end of the cricket season in comparison to the start of the cricket season as portrayed in Table 2. Although the above may explain the difference in absolute muscle thickness of the OI and OE at rest, it should be noted that activation levels between the non-dominant OI and the dominant OI in asymmetrical ASLR L and ASLR R activity positions was not statistically significant.

During a symmetrical activity position (ADIM) the activation of the non-dominant OI is greater than that of the dominant side. Although this finding is only statistically significant for the pre-season measurements on OI, all other activation findings for OI and TA during the ADIM shows that the non-dominant side abdominal muscles are activated to a higher degree than the dominant abdominal muscles. This may emphasise the repeated utilisation of the non-dominant TA and OI during the bowling action, and the subsequent preferential recruitment.[39] The asymmetry of the bowling action may play a role in the development of habitual movement patterns maintained by pre-programmed motor control pathways.[40]

Furthermore, the activation of TA is higher than the activation of OI in the ADIM, ASLR L and ASLR R activity positions, which indicate that the TA is the preferential muscle recruited during sub-maximal muscle contraction.[24,41]

During asymmetrical activity positions the left TA showed statistically significant greater activity during the ASLR R, than the right TA during ASLR L as shown in Fig. 1. This is also clear during the ASLR L, where the left TA activity is again much higher than the right TA activity during ASLR R; although not statistically significant it is of clinical significance. This finding indicates that the left TA activity is higher than the right TA activity during contra-lateral as well as ipsilateral activity positions. This finding is contradictory to a study done by Teyhen *et al.*(2009)[26] which found that the TA is symmetrically activated during asymmetrical activity, while Hu *et al.*(2012)[38] found that TA and OI showed greater asymmetrical activity than OE. The difference in results can be accounted to the different populations studied, where Teyhen *et al.*(2009)[26] studied Department of Defence healthcare beneficiaries, including active-duty military family members, and retirees while Hu *et al*.(2012)[38] studied a group of females. Both authors did not specify details on specific sports participation. The difference in dominant and non-dominant TA activity is less pronounced during the pre-season measurements, which may again show that the intense training and repetition of the asymmetrical bowling action that takes place during a cricket season may be responsible for the preferential increase in activation of non-dominant TA.

A limitation of this study is that no comparison group consisting of non-athletes were assessed parallel to the pace bowlers in this study. Generalisation of the current findings is thus limited to cricket pace bowlers and future studies should be performed to compare abdominal muscle absolute thickness and activity in different sporting populations. Furthermore, studies should be done which assess the training components of the cricket season, the activation of the abdominal muscles during the pace bowling action and establish its influence on abdominal muscle thickness.

Conclusion

This study highlights the possible muscle adaptations in absolute muscle thickness and activity as a consequence of the high load, asymmetrical bowling action which is performed repeatedly during matches and training. The type and intensity of training that took place during the cricket season may have accounted for the asymmetries in abdominal muscle thickness that was found at the end of the season.

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2. Linking Notes between Chapter 7 and Chapters 2 to 6

This section contains information to clarify the link between Chapter 7 and Chapters 2 to 6. In depth discussions in findings of individual papers are in the discussion sections of each paper, while an overall discussion follows in Chapter 8.

The abdominal musculature of the pace bowler adapts to the demands of the repetitive pace bowling action. These adaptations in terms of muscle thickness and activity, including preferential, asymmetrical hypertrophy of OI, OE and TA, are shown in Chapter 7.

In the same way that the abdominal muscle thickness as an intrinsic factor may show certain adaptations in the pace bowler (Chapter 7), it is hypothesised that other intrinsic factors as investigated in Chapters 2, 3 and 6 may also show certain adaptations unique to the pace bowler. Also all intrinsic factors investigated including static balance, dynamic balance, lumbo-pelvic movement control (Chapter 2), lumbar proprioception (Chapter 3), knee proprioception (Chapter 6) and abdominal muscle thickness (Chapter 7) may be interrelated with the specific kinematic variables (Chapters 4 and 5). In this way, the study of the abdominal musculature in Chapter 7, relates to the injury focus of Chapters 2, 3 and 4 as well as the performance based research of Chapters 5 and 6.

CHAPTER 8 – Discussion

1. Introduction to the Discussion

In Chapter 8 an overall discussion of the implications and significance of Chapters 2-7 in the light of the literature (Chapter 1) is presented. Six original papers investigating intrinsic factors in pace bowlers were included in this thesis. The first three papers investigated the association between intrinsic factors and injury. Paper 1 found that performance in the SLBT and the SEBT as measured at the start of the season was better in bowlers who did not sustain an injury during the season. In Paper 2 it was established that lumbar reposition error, as measured in two planes (sagittal and frontal) and in three different positions (neutral lumbar spine, front foot placement and ball release), was associated with general injuries, injuries sustained during the bowling action and especially, low back injury sustained in the past. Paper 3 showed that the range of flexion between front foot placement and ball release at L1 is greater in the non-injured group than in the injured group and that bowlers who did not sustain an injury during the season displayed more flexed knee angles than those who sustained an injury.

The next two papers interrogated the link between intrinsic factors and performance. Paper 4 found that a more extended knee angle, a larger arm to thorax angle, larger L1, T10 and T7 segmental spinal lateral flexion and more global trunk left rotation were positively correlated with higher ball release speeds. Additionally, smaller global trunk flexion angles as well as a smaller change in global trunk flexion angle between front foot placement and ball release was associated with faster ball release speeds. In Paper 5 no correlations between front knee angle, knee reposition error, as a measure of proprioception, and ball release speed could be established.

The sixth paper described the abdominal muscle adaptations in the pace bowler and the major findings were as follow: The absolute muscle thickness and activity of the non-dominant OI was higher than that of the dominant OI; absolute thickness of the dominant OE at rest was significantly higher at the end of the season compared to at the start of the season; and during active straight leg raise on the right, the activity of the left TA is significantly higher than that of the right TA during active straight leg raise on the left.

The discussion in Chapter 8 will revolve around the nature of the pace bowling action, injury, performance, intrinsic factors and physical adaptations as a result of the pace bowling action. The use of valid, reliable and user-friendly physical tests, the relevance of a targeted analysis of the power phase of the bowling action, the value of longitudinal studies and the importance of the alignment with existing injury prevention programmes are discussed. More detailed and focussed discussion sections can be found in the discussion section of each respective paper.

2. Nature of the Pace Bowling Action

The inherent high load nature of pace bowling predisposes the pace bowler to injury which is supported by the high prevalence of injuries in this thesis (Chapters 2, 3 and 4) and other studies (Mansingh et al 2006; Orchard et al 2006; Stretch et al 2009; Stretch and Raffan 2011; Frost and Chalmers 2012). Pace bowling is a non-contact activity, but injury rates are similar to that of other contact sports (Seward et al 1993). Related to the fact that pace bowling is a non-contact activity, the causes of injury are mostly due to the self-imposed mechanical stress a bowler exerts on his own body through efforts to increase bowling performance (Crewe et al 2013b). The pace bowling action consist of a sequence of biomechanical movements and forces which is placed upon the spine (Ferdinands et al 2009)

and lower limbs (Kulas et al 2010). Due to this inherent high load nature of pace bowling which predisposes the bowler to injury and the consequential high incidence of injuries, research on factors associated with injury in pace bowlers is crucial. Therefore, the first step in any research aiming to establish factors associated with injury is the adoption of a clear definition of injury.

3. The Definition of Injury

Because Chapters 2, 3 and 4 were purposefully designed not to be prevalence or injury surveillance studies and the aims of these studies were not to compare results among different countries, it was possible to adopt a targeted definition of injury. For this reason the definition of injury as recommended in the consensus statement paper of Orchard et al (2005) was not used. The definition of Orchard et al (2005) uses the term "any medical condition" which will also capture playing time missed due to conditions other than musculoskeletal injury. Their definition of injury also refers specifically to matches missed, which excludes those injuries that causes training time to be missed (Orchard et al 2005). The definition of injury that was used in this thesis, allowed for capturing a wider variety of injuries as injuries affecting match participation as well as participation in training, are included. It also specifies "musculoskeletal conditions" and in that way excludes general "medical conditions" that may result in non-participation or consultation of a medical practitioner. More detail on the definition is available in the literature review (Chapter 1, Section 2.3, "Definition of Injury"). By using this definition it was hoped to include bowlers suffering from "pain" as this is encompassed by Roussel et al's (2009) definition in that it is a "musculoskeletal condition" that limits participation. Thus it was not considered necessary to explicitly differentiate between "injury" and "pain" in this definition.

4. Low Back and Lower Limb Injuries

Although in injury prevalence research in cricket, injuries to the trunk, back and lower limbs are grouped together (Orchard et al 2002; Mansingh et al 2006), however for purposes of this thesis, it was decided to group low back and lower limb injury together for the following reasons: most studies in cricket pace bowlers focused on the influence of various intrinsic factors on low back injury as the low back is an especially vulnerable area in pace bowlers (Foster et al 1989; Elliott et al 1992; Dennis et al 2008; Stuelcken et al 2008); furthermore, lower limb injury was included into the analysis due to the connection between the low back and lower limbs via the kinetic chain (Kulas et al 2010). It was therefore argued that the high load placed on the lumbar spine predisposes low back as well as the lower limb to injury as the relative angle between segments has a significant effect on the way segments interact in the kinetic chain (Kulas et al 2010). The interrelationship between proximal and distal segments has been confirmed by Crewe et al (2013b) who found an association between a more extended front knee during the front foot contact phase and lumbo-pelvic shear forces.

As a result of the magnitudes and directions of motion-dependent interactive moments which lead to differences in the way segments interact, the influence of the intrinsic variables studied in this thesis (static balance, dynamic balance and lumbar proprioception), may play a role in influencing injuries sustained especially to the low back and lower limb. It follows that the identification of intrinsic risk factors for injury in the low back and lower limb takes priority.

5. Interrelationship between Intrinsic and Extrinsic Factors

The focus of this thesis was on the association of intrinsic factors (static balance, dynamic balance, lumbo-pelvic movement control, lumbar proprioception, spinal and knee angles)

with injury as well as the association of intrinsic factors (spinal and knee kinematics, knee proprioception) and bowling performance. This approach was purposefully undertaken due to the lack of research into these variables and because of the potential that intrinsic factors may have in the predisposition to injury and the effect on performance. However, the importance of extrinsic factors should not be disregarded as Meeuwisse (1994) describes: the bowler is exposed to extrinsic factors in the presence of predisposing intrinsic factors. The repetitive performance of the high load pace bowling action predisposes the bowler to injury, but the associated intrinsic factors, namely lumbar proprioception (Chapter 3), static and dynamic balance (Chapter 2), play a role in the predisposition to injury. Taking into account that the pace bowling action places so much strain on the lumbar spine, minor and asymptomatic injuries may lead to deficits in lumbar proprioception which increase the risk of injury (Pinsault et al 2010). Even pace bowlers, that seem to be injury free, may present with intrinsic factors predisposing them to injury, which increase the risk even more in the presence of extrinsic factors. It is for this reason that attention should be paid to three strategies of injury prevention namely, strategy 1: extrinsic factors; strategy 2: technique-related intrinsic factors; and strategy 3 (as a consequence of the body of work emanating from this thesis): intrinsic factors associated with both reduced injury and improved performance.

6. The Three Strategies of Injury Prevention in Pace Bowling

In conducting the research contained in this thesis, the presence of three strategies of injury prevention in pace bowling became apparent to the author. Prevention of injury via the restriction of extrinsic factors can be regarded as “strategy 1” injury prevention, while technique-related intrinsic factors which may prevent injury at the expense of performance can be seen as “strategy 2” injury prevention. Neuromuscular-related intrinsic factors which

prevent injury and at the same time optimise performance can be classified as “strategy 3” injury prevention. The focus of this thesis was on modifiable strategy 2 and strategy 3 intrinsic factors.

Although extrinsic factors were not studied as part of this thesis, some research has been conducted in the “first strategy” that is extrinsic factors especially when related to over-bowling (Dennis et al 2003). Technique-related intrinsic factors included in the “second strategy” have been researched by Foster et al (1989), Portus et al (2004) and Loram et al (2005) to name a few. These authors studied different variables than the intrinsic factors that were investigated in Chapters 4 and 5 of this thesis. Included in the “third strategy” of injury prevention, intrinsic factors associated with injury (Foster et al 1989; Elliott et al 1992; Portus et al 2004) and performance (Elloitt et al 1986; Portus et al 2004; Loram et al 2005; Wormgoor et al 2010) have been studied, although again these are different variables than what was included in Chapters 2, 3 and 6 of this thesis.

7. Technique-Related Intrinsic Factors

The main function of the pace bowling action is to bowl at a speed of 120km/hr and above and at the same time deliver the ball accurately (Frost and Chalmers 2012). Technique-related factors are often intrinsic factors that predispose the bowler to injury, but at the same time are crucial for faster ball release speeds and can therefore be included as part of the “second strategy” of injury prevention. Performance is important to the pace bowler and some of the same kinematics associated with performance are also associated with injury (Chapters 4 and 5). The following variables were found to be both associated with injury (Chapter 4) and performance (Chapter 5):

- A more extended front knee angle at front foot placement was associated with faster ball release speeds (Chapter 5), while at the same time pace bowlers that did not sustain a lower quarter injury during the cricket season, bowl with a more flexed knee at the start of the season (Chapter 4).

- In order to increase ball release speed, bowlers limited the amount of global trunk flexion (Chapter 5), while bowlers who sustained injuries during the cricket season bowled in a position of global trunk extension and those who did not sustain injuries bowled in a position of flexion when measured at the start of the cricket season (Chapter 4). Differences at the start of the season, when all bowlers were still injury free, may indicate predisposing factors to injury, while differences at the end of the season may indicate an adaptation in movement patterns as a result of injury.

- The smaller the change between global trunk flexion between front foot placement and ball release the higher the ball release speed at the start of the season (Chapter 5), while in non-injured bowlers the range of flexion at L1 was greater than the injured bowlers as measured at the end of the season (Chapter 4). Thus at the start of the season, in order to bowl faster, a bowler has to limit the amount of trunk flexion that takes place between front foot placement and ball release, while at the end of the season those who sustained injuries utilise a smaller range of global trunk flexion than those who do not sustain an injury. It may be that those who sustained injuries attempted to also bowl higher ball release speeds and even though they sustained an injury during the season, maintained the lower range of global trunk flexion, while the injury free bowlers utilised a larger range of global trunk flexion as a natural form of protection of the lumbar spine.

A balance should be created between limiting the intrinsic factors associated with injury and improving the intrinsic factors associated with performance (Bartlett et al 1996). This can cause internal conflict in the bowler, where the bowler will go to great lengths to attain high ball release speeds, but at the expense of injury. The reverse is also true: a bowler may consider limiting the kinematic variables that predispose him to injury, but that will mostly have to be done at the expense of performance. Note however that, not all factors necessitate a trade-off between performance and injury. It is a major recommendation of the present thesis that a focus to identify factors that promote both performance and prevent injury be made. In circumstances where such a trade-off is however inevitable, it is my contention that the recommendations of Bartlett et al (1996) be adopted.

8. Neuromuscular-Related Intrinsic Factors

The pace bowling action is by nature a high load action and intrinsic factors including static balance, dynamic balance, and lumbar proprioception may protect the bowler against injury. According to the literature these variables are associated with improved performance in other sports (Lin et al 2006; Bressel et al 2007; Pinsault and Vuillerme 2009). By improving static balance, dynamic balance, and lumbar proprioception, there is the potential that performance (ball release speed and bowling accuracy) may be improved in pace bowlers. This would form the "third strategy" of injury prevention. It should however be noted that sport-specific adaptation of these variables does take place (Bressel et al 2007) and that findings applicable to other sports may not be generalised to pace bowlers. Therefore studies pertaining specifically to pace bowlers may contribute to injury prevention in cricket pace bowlers in the future.

None of the lumbo-pelvic movement control tests was able to discriminate between bowlers who sustained an injury during the season and those who did not. It was however hypothesised that some of these tests will be able to discriminate at the start of the season between those bowlers who are susceptible to injury and those who are not. It was also felt that performance in the lumbo-pelvic movement control tests would have been worse at the end of the cricket season in those bowlers who did sustain injuries during the season than those who did not (Comerford and Mottram 2001; O'Sullivan 2005). These lumbo-pelvic movement control tests were not tested in a group of pace bowlers before and the unique population may have been a cause for the controversial results due to specific neuromuscular adaptations applicable to pace bowlers. This emphasises the need for research specifically in pace bowlers as opposed to the use of research findings from other sports in injury prevention programmes for pace bowlers.

Other intrinsic factors that were found to be associated with injury in this thesis (Chapter 2 and 3) as well as in the literature (Foster et al 1989; Elliott et al 1992; Dennis et al 2008; Stuelcken et al 2008) provide an opportunity for inclusion in studies similar to the above with the main aim of establishing an association with performance.

9. Extrinsic Factors

Even though the investigation of extrinsic factors was not included in this thesis, it is important to mention as "strategy 1" factors play a crucial role in the development of comprehensive injury prevention programmes. Although various extrinsic risk factors have been studied (Foster et al 1989; Dennis et al 2003) and implemented as injury prevention guidelines (Stretch and Gray 2013), pace bowling injury rates remain high (Stretch et al 2009; Stretch and Raffan 2011). The implementation of extrinsic injury prevention guidelines

for example limiting the number of overs bowled in a match, is very important and should certainly be advocated. However, perspectives within the coaching team may clash where those with a performance-perspective may value practising by repetition of the bowling action as important for better performance, while those with an injury prevention-perspective may advise bowlers to use "relative rest" to either prevent bowling related injury or allow for optimal rehabilitation of past injury. The bowler himself may also experience conflict as the bowler has a strong need to improve his performance, but at the same time need to stay injury free which in itself is crucial for optimal performance.

10. Physical Adaptation as a Result of the Bowling Action

Although the aim of Chapter 7 was not to investigate the association between abdominal thickness and performance or injury, this paper shows abdominal muscle status in terms of thickness at the start and again at the end of a cricket season. Preferential hypertrophy of OI is a consequence of the asymmetrical bowling action. The pace bowling action not only predisposes the bowler to injury, but adaptations resulting from the nature of the pace bowling action, including preferential, asymmetrical hypertrophy of OI, OE and TA, as shown in Chapter 7, may affect the risk of injury (Engstrom et al 2007), it may also serve as a protective mechanism (De Visser et al 2007; Kountouris et al 2013) or it may indicate the need for bowling technique modification (Crewe et al 2013a). However most studies are related to QL asymmetries while in depth exploratory studies in OI, OE and TA are lacking. By establishing the unique adaptations of intrinsic factors in the pace bowlers, health and rehabilitation professionals can be made aware of these factors which will influence the assessment and clinical reasoning processes.

In the same way that the abdominal muscle thickness as an intrinsic factor may show specific adaptations in the pace bowler (Chapter 7), it is hypothesised that other intrinsic factors as investigated in Chapter 2, 3 and 6 may also show specific adaptations. Also all intrinsic factors investigated including static balance, dynamic balance, lumbo-pelvic movement control (Chapter 2), lumbar proprioception (Chapter 3), knee proprioception (Chapter 6) and abdominal muscle thickness (Chapter 7) may be responsible for, or be a results of, the specific kinematic variables as well as the association between these kinematic variables, injury and performance (Chapter 4 and 5).

11. The Use of Valid, Reliable and User-Friendly Physical Tests

Clinical assessment of relevant intrinsic factors may impose challenges in replicated sport-specific positions and the accessibility to valid, reliable and user-friendly tests that could be used by everyday sports health practitioners, is limited. In Chapter 2 the SLBT and SEBT were used to assess static and dynamic balance, respectively, in pace bowlers. Both these tests are easy to perform and do not require any expensive equipment. Other user-friendly tests often used clinically should be tested for reliability, validity and the ability to predict injury or functional level. Should the utility of such tests be confirmed, these tests can be included into injury prevention programmes.

In contrast, the kinematic or electrogoniometric testing of lumbar and knee proprioception requires expensive equipment which is not accessible to the average health professional. Furthermore, in the studies of the present thesis a high speed kinematic camera was used to establish the exact front foot placement and ball release positions of the pace bowling action. Clinically, knee joint position sense can be tested by the use of a long arm handheld goniometer (Piriyaprasarth and Morris 2007) and lumbar joint position sense by the use of an

inclinometer (Cupon and Jahn 2003). Unlike in the studies of this thesis, the clinical assessment of joint position sense usually does not occur in sport specific positions, as a high speed camera may not be available, but can still be done in arbitrary pre-determined positions.

12. The Targeted Analysis of the Power Phase of the Bowling Action

The lumbar proprioception (Chapter 3), spinal and knee kinematics (Chapters 4 and 5) and knee proprioception (Chapter 6) were tested in two functional, bowling-specific positions, namely front foot placement and ball release, which indicates the start and end of the power phase or front foot placement phase. Contrary to previous research which focused on the back foot placement phase, it was decided to investigate the front foot placement phase in this thesis for the following reason: kinetic forces, including power, torque and ground reaction forces are the highest during the power phase, thus between front foot placement and ball release (Foster et al 1989; Ferdinands et al 2009). Due to the high kinetic forces in the power phase, it is also the phase where injury is most likely to be sustained. Furthermore, due to the fact that the classification of pace bowlers as mixed or non-mixed depends mainly on kinematics during the back foot contact phase (the phase preceding the front foot contact phase or power phase), it was decided not to classify bowlers as having mixed or non-mixed bowling actions in this study. Also, it has been suggested that bowlers are all in roughly the same position before the high load power phase starts as no difference in alignment of the thorax relative to the pelvis has been found (Ranson et al 2008; Stuelcken et al 2010) (this point is discussed in more detail in the literature review Section 5.2 (“Classification of the Pace Bowling Action “).

13. The Value of Assessments at both the Start and the End of a Cricket Season

Assessments that are performed at both the start and then repeated at the end of a cricket season may be indicative of a cause-effect relationship between variables and their predicted outcomes, which is not possible in cross-sectional studies. In addition, such a longitudinal approach to the assessment and reassessment of variables, allows for the effects of different in season factors to be assessed independently. The intrinsic factors described in Chapter 2, 4, 5 and 7 were tested at both the start and the end of the season. In order to provide a targeted analysis of the usefulness of such an approach the findings from Chapter 2 will be used here to show the value of doing assessments at the start and again at the end of a cricket season.

Performance in the static and dynamic balance tests was worse amongst bowlers who sustained an injury during the cricket season compared with those who did not (Chapter 2). This finding was only true for measurements taken at the start of the cricket season and not at the end of the cricket season, which may indicate that static and dynamic balance tests (especially when weight bearing on the right leg) predict the incidence of low back and/or lower limb injury. As this difference was not found at the end of the cricket season, the assumption can be made that poor SLBT and SEBT scores may be related to factors which varied during the cricket season, such as training, fatigue, or physiological changes to proprioception (for example), but the scores were not affected by injury, where no statistically significant difference was found between the two groups in terms of previous injury.

In Chapter 3 static and dynamic balance as well as lumbo-pelvic movement control showed improvement when it was measured again at the end of the cricket season which suggests that

the training that took place during the season may have been responsible for this improvement. Although the analysis of activities that took place during the off season was outside the scope of this study, the findings in Chapter 2 may lead us to the recommendation that the training of intrinsic factors, including static and dynamic balance during the off season, may prevent injuries during the cricket season. However, before making inferences on results, it should be noted that some tests may have poor test-retest reliability and for this reason cannot be used as a reliable clinical measure of improvement in balance (Clark et al 2010).

14. Alignment with Existing Injury Prevention Programmes

It is important for South African sports health care professionals (the local context of to the current thesis) to be globally competitive as well as locally responsive when it comes to injury prevention. Stretch and Gray (2013) have developed an injury prevention programme for South African pace bowlers which incorporates screening, physical preparation, over-bowling and technique modification, which is known as the SPOT injury prevention programme. This is a comprehensive programme which covers all three strategies of injury prevention and has many synergies with the data and recommendations emanating from the current thesis. “Strategy 1” (extrinsic factors) links with “over-bowling”, while “strategy 2” is aligned with “technique”. Intrinsic factors which reduce injury and optimise performance (“strategy 3”) can be classified under “screening” and “physical preparation”. The intrinsic factors studied in this thesis thus support the further development of the SPOT injury prevention programme.

15. Conclusion to the Discussion

This discussion emphasised that the inherent high load nature of the pace bowling action predisposes the bowler to injury. The prevalence of injuries amongst pace bowlers are high and for this reason injury prevention is crucial. It is recommended that comprehensive injury prevention programmes consist of three strategies namely: 1. Extrinsic factors; 2. Technique-related intrinsic factors (injury prevention at the expense of performance); 3. Neuromuscular-related intrinsic factors (injury prevention and at the same time optimisation of performance). A conclusion to this thesis, significance, strengths, limitations, future research and clinical recommendations will follow in the next chapter.

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CHAPTER 9 – Conclusions

1. Conclusions

The inherent nature of the pace bowling action predisposes pace bowlers to injury. This is confirmed by the high prevalence of injuries in pace bowlers that occur as a result of the pace bowling action. This high injury prevalence rate is emphasised since pace bowling is a non-contact activity but injury rates are comparable to contact sports. The pace bowling action contains biomechanical elements that are associated with injury for example knee extension angle during the power phase. These elements are inherent to the pace bowling action and are needed to attain faster ball release speeds, and subsequently, are needed to optimally fulfil the role of the pace bowler in the cricket team.

Guidelines which incorporate a combination of the proposed injury prevention strategies (1, 2 and 3), emanating from this thesis may be successful in decreasing the high risk of injuries that the pace bowling action imposes on pace bowlers. The presence of intrinsic factors related to neuromuscular constituents (poor static balance, dynamic balance and lumbar proprioception) while the bowler is exposed to extrinsic factors like a high bowling workload predisposes the bowler to injury.

Although the investigation of extrinsic factors was not within the scope of this thesis, extrinsic factors interact with the intrinsic factors and should also independently form an essential part of a comprehensive injury prevention programme. Adherence to a comprehensive injury prevention programme containing all three vital strategies may allow the pace bowler to safely perform the pace bowling action and its dangerous components while at the same time achieving optimum performance.

The second strategy of a comprehensive injury prevention programme includes the interrogation of technique-related intrinsic factors. These factors have been studied and recommendations have been made by other authors based on these intrinsic factors' association with injury. In this thesis two kinematic variables were found to be associated with incidence of injury (Chapter 4) and at the same time with higher ball release speeds (Chapter 5). A more extended knee angle as well as a position of trunk extension is associated both with increased ball release speeds as well as with injury. Injury prevention "strategy 2" is regarded as important, but may be difficult to achieve as the pace bowler may not be motivated to adopt injury prevention measures at the expense of greater ball release speeds. Another problem is the conflicting viewpoints of different members of the coaching team in terms of the balance between injury prevention and performance. These problems make implementation of these intrinsic injury prevention factors difficult and may negatively impact on the success of implementation of such an injury prevention programme.

Intrinsic factors related to neuromuscular constituents are a focus of the third proposed strategy to prevent injury. In this thesis, intrinsic factors like improved static and dynamic balance ability (Chapter 2), and improved lumbar proprioception (Chapter 3) are associated with decreased low back and lower limb injury rates. In the literature, these same intrinsic factors have been associated with improved performance in other sports. It should thus be established whether these intrinsic factors are associated with increased performance specifically in pace bowlers. If this is the case, then static balance, dynamic balance, and lumbar proprioception should be included in injury prevention research. If the injury prevention programme containing these intrinsic factors is found to be effective in prevention of injury, this may contribute to injury prevention in pace bowlers. Moreover the bowler may

be more motivated to adhere to the programme, while both the coaches' and the health professionals' goals will be met.

Not only the association between intrinsic factors and injury, but also the association between intrinsic factors and performance should be investigated. Although it was hypothesised that knee proprioception will be associated with faster ball release speeds, this association was not found (Chapter 6). In the literature on other sports, better proprioception is associated with a decrease in injuries. If a positive association could have been established in Chapter 6, where better proprioception results in faster ball release speeds, then this would have been the ideal intrinsic factor to emphasise as part of an injury prevention programme. Intrinsic factors associated with better bowling performance, like knee proprioception, should be used in studies to establish if these factors are associated with decreased injury rates in pace bowlers.

Sport-specific adaptation of intrinsic factors, such as the modifications to abdominal musculature, takes place due to the repetitive and high load pace bowling action, especially the non-dominant OI was thicker than the dominant OI when measured at the start as well as at the end of the cricket season (Chapter 7). These adaptations may either predispose the bowler to injury or protect the bowler against injury. Intrinsic factors may be incorporated into injury prevention and performance enhancement programmes while taking into account the various anatomical adaptations, for example in muscle thickness, which is unique to the pace bowler.

2. The Significance of the Studies Contained in this Thesis

The significance of the studies contained in this thesis lies in the associations found between intrinsic factors (static balance, dynamic balance, and lumbar proprioception) and injury,

which have never before been studied in amateur pace bowlers. The findings in Chapter 2 and 3 provide the opportunity for these factors to be assessed for an association with performance in future studies and if this association is found, should be included into injury prevention programmes. Furthermore, the association between technique-related kinematic variables (knee and spinal angles) and injury (low back and lower limb) (Chapter 4), as well as the association between these same technique-related kinematic variables and performance (ball release speed)(Chapter 5) in amateur pace bowlers, emphasises the presence of technique-related intrinsic factors which can be modified to prevent injury at the expense of performance. Also, by describing the abdominal musculature of amateur pace bowlers at the start and at the end of the season, it is shown that this specific intrinsic variable is unique in pace bowlers and adapts to the sport-specific demands of the pace bowling action. The specific population of male, amateur, pace bowlers, chosen for inclusion in this thesis is a vulnerable group due to the limited access they have to health and rehabilitation services. The longitudinal follow up component of this study adds to this thesis' value in that cause-effect inferences can be made and changes in intrinsic factors over time can be determined. The investigation of both low back and lower limb injury are important due to the interconnectedness of these body areas in the kinetic chain. This thesis makes a meaningful contribution to the development of comprehensive injury prevention programmes through the suggestion of three strategies of injury prevention namely extrinsic factors, technique-related intrinsic factors where injury is prevented at the expense of performance and neuromuscular-related intrinsic factors where both injury and performance are optimised. Moreover, the investigation of intrinsic factors in pace bowlers with the aim to prevent injury are aligned with the current SPOT (screening, physical preparation, over-bowling, technique) injury prevention programme advocated by the South African United Cricket Board. Intrinsic

factors studied in this thesis fall under the categories of physical preparation and technique, and should be further explored in future studies.

3. Strengths

The longitudinal nature of Papers 1, 3, 4 and 6 differ from most previous research that are largely cross-sectional investigations. Longitudinal assessments are less susceptible to factors which vary from day to day and therefore longitudinal studies are less prone to spurious conclusions. In addition, the longitudinal approach has allowed for tracking the relationship of variables over time, an approach which is rare in cricket research. It is therefore likely that these data further add to the quality of our understanding to injury prevalence. The low dropout rate in these papers is of further value as a low dropout rate enhances the value of the longitudinal follow up component.

Furthermore, the prospective monitoring of injuries (Papers 1, 2 and 3) reduces recall bias and increases the accuracy of the injuries reported. A more accurate reflection of the status of injuries allows for better planning of preventative measures.

The objective outcome measures used namely the electrogoniometer in Papers 2 and 5, the kinematic analysis system in Papers 3 and 4 as well as the rehabilitative ultrasound imaging used in Paper 6 are considered as strengths of these papers. Scientific inferences that are based on measures made by objective outcome measures can be converted into sound, clinical recommendations.

Measurements namely joint position sense and kinematics taken during the power phase of the fast bowling action as done in Papers 2, 3, 4 and 5 are of immense value as this is the

phase during the bowing action where kinetic forces are the highest while most previous studies researched the kinematics of the back foot contact phase.

Despite the advantages of the studies detailed above, a number of limitations must necessarily be acknowledged in the interest of improved study design in subsequent research, as described hereafter.

4. Limitations

The activities that took place during the off season were not analysed in this thesis. The two groups of bowlers – those who sustained injuries during the season and those who did not were similar in terms of demographic and previous injury related variables at the start of the season. An attempt was made to create a homogenous group of pace bowlers by applying a stringent inclusion and exclusion criteria in that all bowlers were injury free, playing at the same level (amateur) and were within a narrow age range (18 to 26 years). It is for this reason that the influence of off season activities should have had a minimal effect on the results obtained in this thesis. It is however recommended that off season activities should be considered in future research.

Although the studies in this thesis have generally achieved sample sizes comparable to or larger than most other similar studies, another limitation is the reduction in the number of participants in Chapter 3 (n=17) and Chapter 6 (n=11), while the number of participants in Chapters 2 (n=32), 4 (n=31), 5 (n=31) and 7 (n=26) is almost double. This difference in number of participants in the two papers was due to limited access to the electrogoniometry when collecting data for Chapter 3. Consequently, changes in lumbar proprioception could

not be measured and compared at the end of the cricket season, which limited the inferences that could be made from the results.

An unavoidable limitation of Chapter 4 and 5 is the method of kinematic analysis used. It is a well-known fact that due to the use of skin markers, the movement of the skin cannot be controlled for, and this may increase the error in the data. This limitation can be overcome by the use of bone pins; however, this is an invasive method and would not have been approved by the University of the Witwatersrand Human Research Ethics Committee.

Although for both Chapters 3 and 6 functional, sport specific positions were used in order to, as closely as possible, mirror the of the bowling action, these bowling specific positions were replicated into a static position. It would be ideal for joint position sense to be tested in positions where high speed is replicated at an automated level, and not merely tested in a static position where the demands of the sport are not optimally replicated. The methodology behind such a study is complicated if not impossible.

The study in Chapter 7 did not investigate muscle activation during the pace bowling action and assumptions are based on abdominal muscle activation in arbitrary activity positions. Results found in this study were not compared to a sedentary, non-sporting population, but assumptions were based on and compared to findings in the literature.

5. Future Research Recommendations

It is recommended that all four spheres of the current South African injury prevention programme, SPOT (screening, physical preparation, over-bowling, technique), be investigated in the context of the data presented and inferences suggested in the present

thesis. As part of "screening", factors predicting injury are ideally investigated, so that these factors can be identified and can be corrected before injury occurs. Furthermore, extrinsic factors and specifically the effect of "over-bowling" on injury rates could be investigated as part of comprehensive injury prevention programme development. "Technique-related" factors associated with injury and performance could be investigated further via kinematic and kinetic methodologies.

The assessment of intrinsic factors (emanating from this thesis) associated with injury in pace bowlers have the potential to be incorporated in the "physical preparation" sphere of the SPOT injury prevention programme. The ideal will be if these intrinsic factors are associated with a decrease in injuries and at the same time with an improvement in performance. Future research could thus be performed as a first step where injury- and performance-related intrinsic factors from this thesis, from previous research on pace bowlers as well as from research on other sporting populations are identified. These intrinsic factors could then be tested for associations with lower injury rates and at the same time for associations with better performance. This can be done through cross-sectional research designs. Intrinsic factors which are associated with both decreased injury rates and at the same time with better performance could be included into injury prevention programmes. These injury prevention programmes could be tested for effectiveness in preventing injuries in pace bowlers as part of longitudinal follow up studies.

It is furthermore suggested that the interrelationship of intrinsic factors, including lumbo-pelvic movement control, static balance, dynamic balance and lumbar proprioception, in the kinetic chain be investigated in future studies. The more proximal intrinsic factors (lumbo-pelvic movement control and proprioception) may alter movement patterns of the distal

segments (upper and lower limbs), while static and dynamic balance of the lower limbs may affect the movement of the upper limbs. Also, although the association between front knee angle, knee proprioception and ball release speed was not found in Chapter 6, other intrinsic factors associated with the ability to position the knee in a position that will optimise ball release speed could be investigated. At the same time the role of intrinsic factors in front knee angle position could be investigated relative to injury prevention as a more flexed knee has been associated with a lower risk to injury (Chapter 4). An investigation on the role of these intrinsic factors as part of the kinetic chain may clarify many assumptions on movement-related issues.

Additionally, electromyography studies have the potential to establish the role of different muscles during the pace bowling action. The intensity, timing and sequence of activation of the abdominal and lumbar musculature could provide more information to theories related to muscle adaptation.

Studies on the adaptation in abdominal muscle thickness and activity in pace bowlers are lacking. Asymmetrical hypertrophy of the abdominal musculature, as found in the present studies, may serve as a protective mechanism against injury or it may predispose the bowler to injury. Also, the association between abdominal muscle thickness and the predisposition to injury as well as the simultaneous association with performance can specifically be investigated in cricket pace bowlers. Research in this area may provide the opportunity for the development of injury prevention and performance optimisation programmes. Furthermore, the asymmetries in abdominal muscle thickness changed over the course of the cricket season which may be as a consequence of the type and intensity of training that took

place during the cricket season. Further research to investigate the factors or activities that influence abdominal muscle thickness is advocated.

When viewing the results of abdominal muscle thickness and activity (Chapter 7) in context with the literature, it is hypothesised that the more active the population the larger the OI values. Similarly, other intrinsic factors like static balance, dynamic balance, lumbo-pelvic movement control (Chapter 2), lumbar proprioception (Chapter 3) and knee proprioception (Chapter 6) may also be better developed in a more active sporting population like pace bowlers. If activity influences and improve these intrinsic factors, then it may be beneficial to establish the effect of rehabilitation programmes adhered to during the off season.

6. Clinical Recommendations

Cricket is a competitive sport where performance is of utmost importance. The pace bowler is pressured to bowl accurately at a high speed and training is often directed at improving performance. However, for a pace bowler to be able to perform and optimally contribute to the team performance, he has to be injury free. Performance training should thus be balanced with injury prevention measures. The strong need for performance may motivate bowlers to incorporate certain technique-related intrinsic factors into the bowling action to improve performance at the expense of injury prevention. This divergence results in conflicting desires in the pace bowler, as he wishes to stay injury free but also wishes to bowl with a high ball release speed. Also, the bowler may be advised to bowl with a more extended knee for example by those with a performance viewpoint, while those with an injury prevention viewpoint may advise the opposite. The bowler himself may also struggle to find the balance between performance and injury. Technique modification may be effective in protecting the pace bowler against injury, although complete buy in from the bowler may not be achieved

due to the potential negative impact on performance. Nevertheless, technique modification is a means of preventing injury and its importance should not be disregarded. Furthermore, awareness of the technique-related intrinsic factors which are associated with a decrease in injury, but at the same time with improved performance, may deepen the understanding of a possible lack of adherence to the "technique" sphere of the South African SPOT injury prevention programme. This awareness can support comprehensive education on injury prevention.

Not only technique-related intrinsic factors but also intrinsic factors related to other neuromuscular components can be optimised with the aim of preventing injury. The incorporation of training in static balance, dynamic balance and lumbar position sense into injury prevention programmes may be effective amongst the pace bowling population. Additionally, the incorporation of stringent intrinsic injury prevention programmes in combination with extrinsic injury prevention programmes may facilitate the development of injury free pace bowlers.

The intrinsic factors found to be associated with injury in this study, may be incorporated into off season training programmes, as this may provide the pace bowler with the needed neuromuscular control to protect him against injury in the presence of the high load pace bowling action. During the off season, bowling intensity is less than during the cricket season, which provides the opportunity for pace bowlers to improve static balance, dynamic balance and lumbar proprioception so that these neuromuscular components can protect the bowler against injury during the cricket season. Although the studies in this thesis merely searched for associations between injury and intrinsic factors, further research can explore the

detailed interactions of such associations as well as the potential of these factors to prevent injury.

The population of amateur pace bowlers are especially vulnerable to the effects of injury as this group plays on a competitive level, but at the same time does not have easy access to preventative and rehabilitative medical services. Injury prevention education as well as the implementation and promotion of injury prevention programmes like the SPOT programme may lower the injury rates in this group.

CHAPTER 10 – Appendices

Appendix 1 – Sections Removed from Chapter 4 (Paper 3) due to Limitation in Word Count

The following sections were removed from Paper 3 due to the limited word count requested from authors by the journal, *Journal of Science and Medicine in Sport*:

1. Demographic and Previous Injury in Pace Bowlers at the Start of the Cricket Season

Table 1. Demographics and previous injury in bowlers who sustained an injury and those who did not sustain an injury during the cricket season.

	LQ injury (n=17)	**No LQ injury (n=15)**	**p**
Age – (mean, SD)	21.88 (2.03)	21.00 (1.81)	0.68
Fast bowler (n, %)	5 (29%)	6 (40%)	0.40
Fast medium bowler (n, %)	10 (59%)	6 (40%)	0.24
Medium bowler (n, %)	2 (12%)	3 (20%)	0.44
Right handed (n, %)	16 (94%)	10 (67%)	0.06
Openings bowler (n, %)	14 (82%)	11 (73%)	0.38
First change (n, %)	3 (18%)	4 (27%)	0.11
Bowler for 1-3years (n, %)	1 (6%)	0 (0%)	0.53
Bowler for 4-6years (n, %)	0 (0%)	2 (13%)	0.21
Bowler for >6years (n, %)	16 (94%)	13 (87%)	0.45
Previous injuries sustained (n, %)	16 (94%)	12 (80%)	0.25
Previous injury sustained during the bowling action (n, %)	10 (59%)	8 (53%)	0.52
Previous low back injury sustained (n, %)	2 (12%)	2 (13%)	0.65

LQ – low quarter (low back and/or lower limb injury)
Significance: $p<0.05$

At the start of the season, the two groups of bowlers (bowlers who did sustain an injury during the cricket season and those who did not) did not differ in terms of demographic and previous injury variables as shown in Table 1.

2. Spinal Flexion and Extension during the Power Phase

The difference between pre- and post-season findings in injured bowlers was not evident in non-injured bowlers. Ferdinands et al (2009) also found a spinal flexion angle amongst injury free pace bowlers during the power phase. During the power phase although only a moderate percentage (55%) of the available spinal range of movement is used (Ferdinands et al 2009), flexion occurs at a high velocity, which may indicate that much of the flexion will still occur in the follow-through phase due to momentum. In order to create more momentum to increase ball release speeds, the injured bowlers may have chosen the position of extension rather than flexion at front foot placement at the start of the season. An explanation may be that injured bowlers utilise more extension than non-injured bowlers earlier in the delivery phase and by the time they get to front foot placement they are still in extension and not in flexion like their non-injured counterparts (Ferdinands et al 2009). This increase in extension may occur in an attempt to increase ball release speeds. The fact that the power and torque values of both flexion and lateral flexion are in the same direction during the power phase, may indicate high activity in the lumbar spine musculature and consequential large stresses on the low back (Ferdinands et al 2009). As extension was present in the bowlers who sustained injuries at the start of the season, but not at the end of the season, the position of extension may be a factor that predicts lower quarter injury in pace bowlers.

3. Lumbar Angles during the Power Phase

There were no statistically significant differences in spinal angles at the levels of L1, T10 and T7 between the injured and the non-injured group as measured at the start of the season. It should be noted that all bowlers were injury free at the start of the season, which may

contribute to the similarities in spinal kinematics between those who sustained injuries during the season and those who did not. It may also indicate the limited predictive value of spinal angles at L1, T10 and T7.

4. Spinal Rotation during the Power Phase

Although no differences in rotation angles were found in this study, Ferdinands et al (2009) found that controlled left lumbar rotation up to the full available range of movement occurs during the power phase. High power and torque values in combination with high ground reaction forces were found at the start of the power phase, thus also at front foot placement position. This combination of high load kinetics in an end of range rotation position of the low back may reduce the compressive strength of the spine (Panjabi 1992). However, although high power and torque values were present in the power phase, these forces acted in opposite directions, creating the controlled rather than an opposed active rotation to the left. The controlled rotation forces, described by Ferdinands et al (2009), that acted on the lumbar spine may explain why no difference was found in our study between rotation in the injured and non-injured group. Ferdinands et al (2009) found that lower power and torque values occur at times when lower ranges of motion were also measured. Stuelcken et al (2010) also found that between front foot placement and ball release lateral flexion is strongly coupled with rotation. Although rotation was not associated with injury in this study, the relationship between the combination of these two movements and injury may show an association with pathomechanics of the spine (Foster et al 1989; Elliott 2000; Portus et al 2004).

5. The Anatomical Coordinate System

The spinal segment rotations are calculated from local coordinate systems (the origin as the centre of the segment, with the vector in the direction of the next segment) (figure 1). As an example, L1 is the origin and T10 is the direction of the vertical vector (z axis). The x axis is positive to the left. The y axis is pointing in an anterior direction. The anatomical coordinate system was based on the Plug-In Gait model as well as on the International Society of Biomechanics' recommendations (Wu and Cavanagh 1995). Data was produced for the relative angles between segments and were calculated in a Z-X-Y decomposition sequence (Z – axial rotation, X – flexion-extension, Y – lateral flexion) (Ranson et al 2008; Stuelcken et al 2010).

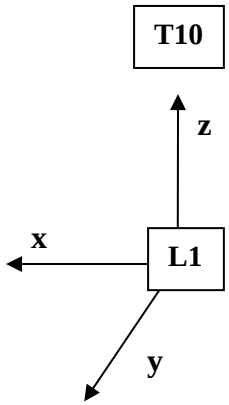

Figure 1. The Anatomical Coordinate System

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Appendix 2 – Pre-season Questionnaire

Study number:_____ **Age:**_____

Which of the following activities do you spend most of your time on during working hours?

☐ Manual labour ☐ Desk- or computer work
☐ Driving ☐ Other, please specify_____

Which type of bowler are you?

☐ Fast bowler ☐ Medium bowler
☐ Fast-medium bowler

At what speed do you usually bowl?

☐ _____km/hr ☐ Not sure

Are you a right or left handed bowler?

☐ Right ☐ Left

What is your bowling position?

☐ Opening bowler ☐ First change
☐ Second change ☐ Third change
☐ Other, please specify_____

For how long have you been a fast bowler?

☐ <1 year ☐ 1-3 years
☐ 4-6 years ☐ >6 years

Are you currently suffering from an injury?

Injury definition: an injury that resulted in loss of at least 1 day of sporting activity OR that occurred during a sporting activity that required medical attention (emergency, physiotherapy, etc)

☐ Yes ☐ No

Have you suffered any previous injury(ies) since you started bowling?

☐ Yes ☐ No

If yes, in which body region was the injury(ies)? (tick more than one if necessary)

Body region	**Injury 1**	**Injury 2**	**Injury 3**
Head or face			
Neck			
Shoulder			
Elbow			
Wrist/hand			
Sternum/ribs/upper back			
Low back			
Hip/groin/buttock			
Knee			
Shin			
Foot/ankle			
Others, please specify:			

On which side of the body did you sustain the injury(ies)?

(write the body region as ticked above under the relevant injury number, then tick one option below each injury)

	Injury 1	**Injury 2**	**Injury 3**
Body region			
Left			
Right			
Both sides			
Not applicable			

How did the injury(ies) occur? (tick one option per injury)

Traumatic: an injury that was caused by being hit by a ball, slipping on an uneven surface, etc

Non-traumatic: an injury that started with no apparent cause

	Injury 1	Injury 2	Injury 3
Body region			
Traumatic			
Non-traumatic			
Other, please specify			

Briefly explain how the injury(ies) happened?

_____

_____

_____

How long were you unable to train for as a result of the injury(ies)? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Training not affected			
< 1 week			
1 - 3 weeks			
4 - 8 weeks			
9 - 12 weeks			
3 - 6 months			
> 6 months			

How many matches were you unable to participate in as a result of the injury(ies)?
(tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Missed > 8 matches			
Missed 7-8 matches			
Missed 5-6 matches			
Missed 2-4 matches			
Missed 1 match			
Missed no matches			
Other, please specify:			

During which part of the season did the injury(ies) occur? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
First two months			
Middle two months			
Last two months			
Outside the season			
Other, please specify:			

Which year did the injury(ies) take place? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
2010			
2009			
2008			
2006-2007			
2004-2005			
Other, please specify:			

How did you manage your previous injury(ies)? (tick more than one if relevant)

	Injury 1	Injury 2	Injury 3
Body region			
Surgery			
Medication			
Physiotherapy			
Strapping			
Wore a brace			
Alternative medicine (chiro,etc)			
Rest			
No treatment			
Others, please specify:			

Did the injury(ies) resolve/clear up/heal completely? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Yes			
No			

How long did it take for the injury(ies) to heal completely? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
< 1 week			
1 - 3 weeks			
4 - 8 weeks			
9 - 12 weeks			
3 - 6 months			
> 6 months			
Other, please specify			

In your opinion, could any of these injuries have been prevented?

☐ Yes ☐ No

If yes, how do you think the injury(ies) could have been prevented?
(tick more than one if relevant)

	Injury 1	Injury 2	Injury 3
Body region			
Protective gear			
Adequate training			
Adequate warm up			
Adequate cool down			
Adequate stretching			
Other, please specify:			

How important is injury prevention to you?

☐ Very important ☐ Not so important ☐ Not important at all

How important is improvement of bowling performance to you?

☐ Very important ☐ Not so important ☐ Not important at all

Have you done any form of training during the last four months (off season)?

☐ Yes ☐ No

If yes, what training have you been doing?

☐ Running ☐ Weight training
☐ Other, please specify:_____

How many times per week?

☐ 1 x per week ☐ 2-4 x per week
☐ >4 x per week ☐ Other, please specify:_____

In your opinion, are you generally under a lot of stress?

☐ Yes ☐ No

If yes, in which area of your life are you experiencing stress?

☐ Personal ☐ Work
☐ Sport ☐ Other, please specify:_____

Appendix 3 – Monthly Injury Surveillance Questionnaire

Study number:_____ **Age:**_____ **Today's date:**_____

Have you suffered an injury during the last month?

Injury definition: an injury that resulted in loss of at least 1 day of sporting activity OR that occurred during a sporting activity that required medical attention (emergency, physiotherapy, etc)

☐ Yes ☐ No

Date(s) of injury(ies):

1._____
2._____
3._____

If yes, in which body region did you suffer the injury(ies)?

Body region	**Injury 1**	**Injury 2**	**Injury 3**
Head or face			
Neck			
Shoulder			
Elbow			
Wrist/hand			
Sternum/ribs/upper back			
Low back			
Hip/groin/buttock			
Knee			
Shin			
Foot/ankle			
Others, please specify:			

How much pain did you experience at the time of the injury?

(0 - refers to no pain; 10 refers to most severe pain imaginable; make a mark on the line on the relevant spot)

Injury 1 0_____10
Injury 2 0_____10
Injury 3 0_____10

How much pain do you have at the moment?

Injury 1 0_____10
Injury 2 0_____10
Injury 3 0_____10

How did the injury(ies) occur? (tick one option per injury)

Traumatic: an injury that was caused by being hit by a ball, slipping on an uneven surface, etc

Non-traumatic: an injury that started with no apparent cause

	Injury 1	**Injury 2**	**Injury 3**
Body region			
Traumatic			
Non-traumatic			
Other, please specify			

Briefly explain how the injury(ies) happened?

_____
_____
_____

During which activity did the injury(ies) occur? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Bowling - training			
Bowling - match			
Batting - training			
Batting - match			
Fielding -training			
Fielding - match			
Other, please specify:			

How many matches were you unable to participate in as a result of the injury(ies)? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Missed > 8 matches			
Missed 7-8 matches			
Missed 5-6 matches			
Missed 2-4 matches			
Missed 1 match			
Missed no matches			
Other, please specify:			

How long were you unable to train for as a result of the injury(ies)? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Training not affected			
< 1 week			
1 - 3 weeks			
4 - 8 weeks			
9 - 12 weeks			
3 - 6 months			
> 6 months			

How did you manage the injury(ies)? (tick more than one option if needed)

	Injury 1	Injury 2	Injury 3
Body region			
Surgery			
Medication			
Physiotherapy			
Strapping			
Wore a brace			
Alternative medicine (chiro, etc)			
Rest			
No treatment			
Others, please specify:			

If you consulted with a medical doctor, what was their diagnosis? _____
(leave blank if a doctor was not seen)

If you consulted with a physiotherapist, what was their diagnosis? _____
(leave blank if a physiotherapist was not seen)

Have you previously suffered the same injury(ies)? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
Yes			
No			

If yes, when did these injuries in the past? (tick one option per injury)

	Injury 1	Injury 2	Injury 3
Body region			
2010 off season			
2009			
2008			
2006-2007			
2004-2005			
Other, please specify:			

Did these injuries resolve/clear up/heal completely? (tick one option per injury)

Body region			
Yes			
No			

In your opinion, could these injuries have been prevented?

☐ Yes ☐ No

If yes, how do you think the injury(ies) could have been prevented?
(tick more than one if relevant)

	Injury 1	Injury 2	Injury 3
Body region			
Protective gear			
Adequate training			
Adequate warm up			
Adequate cool down			
Adequate stretching			
Other, please specify:			

In your opinion, are you generally under a lot of stress?

☐ Yes ☐ No

Have your stress levels changed over the last month?

☐ Increased ☐ Decreased
☐ Stayed the same ☐ Other, please specify:_____

In which area of your life are you experiencing stress?

☐ Personal ☐ Work
☐ Sport ☐ Other, please specify:_____
☐ I don't experience stress

Appendix 4 – Post-season Questionnaire

Study number:_____ **Age:**_____ **Today's date:**_____

Are you currently suffering from an injury?

Injury definition: an injury that resulted in loss of at least 1 day of sporting activity OR that occurred during a sporting activity that required medical attention (emergency, physiotherapy, etc)

☐ Yes ☐ No

How important is improvement of bowling performance to you?

☐ Very important ☐ Not so important ☐ Not important at all

How important is injury prevention to you?

☐ Very important ☐ Not so important ☐ Not important at all

Have you been training outside cricket practice during the past season?

☐ Yes ☐ No

If yes, what training have you been doing?

☐ Running ☐ Weight training
☐ Other, please specify:_____

How many times a week?

☐ 1 x per week ☐ 2-4 x per week
☐ >4 x per week

Looking back at the past season - do you think that the injury(ies) you suffered could have been prevented?

☐ Yes ☐ No

If yes, how do you think the injury(ies) could have been prevented?

☐ Protective gear ☐ Adequate training
☐ Adequate warm up ☐ Adequate cool down
☐ Adequate stretching ☐ Other, please specify:_____

In your opinion, are you generally under a lot of stress?

☐ Yes ☐ No

If yes, in which area of your life are you experiencing stress?

☐ Personal ☐ Work
☐ Sport ☐ Other, please specify:_____

Thank you very much for participation in this research project!

Appendix 5 – Information Sheet and Informed Consent Forms

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences
Wits Medical School, 7 York Road, PARKTOWN, 2193, Johannesburg • Tel: (011) 717 2014 •
Fax: 086 663 5776 • e-mail: benita.olivier@wits.ac.za

2010-08-01

Dear Sir/Madam

My name is Benita Olivier. I am currently enrolled for a doctorate degree in physiotherapy at the University of the Witwatersrand. I am doing research on the association between physical factors, the biomechanical aspects of bowling as well as bowling performance and injury in pace bowlers. I would be most grateful if you would be willing to participate in this research project. The project is scheduled to commence in August 2010 and finish in March 2011.

Why is this study important?

The main aim of this study is to establish the factors associated with injury and performance in pace bowlers. If certain physical risk factors (proprioception, balance, abdominal muscle activity and lumbo-pelvic movement control) can be associated with injury these factors may be addressed in the prevention of injury. If these factors are found to be related to injury, it is possible that they may be related to performance as well. Correction of these physical factors and altered bowling components may hence result in improved performance which is a great motivator for any athlete.

What would the pace bowler be expected to do?

Should you agree to participate, you will be asked to complete a questionnaire and take part in a series of tests. These tests are non-invasive and will not inflict any pain or discomfort. A video analysis of the bowling action will be done and bowling speed will be determined. Tests will include balance and movement tests as well as ultrasound imaging of the

abdominal muscles. Please refer to the last page of this document for a detailed description of the tests to be performed. The entire series of tests will be performed at both the start and end of the season. On the day of testing, you will be required to wear short (above knee) dark ski-pants, a white t-shirt, white socks and bowling spikes. This is necessary for the attachment of light reflective markers to ensure an accurate view of joint movement during video analysis. It is proposed that testing duration will be approximately one hour per bowler.

Throughout the season (8 months), you will be required to report details surrounding injuries sustained. You will be contacted once a month. If an injury was sustained during that month, you will be required to complete a two page questionnaire on the mechanism and management of the injury as well as the number of matches missed.

Participation is completely voluntary and you will be free to withdraw at any time. Should you decide to withdraw from this study, no consequences will be suffered and reason for withdrawal may be withheld.

What are the benefits to the participants?

As participating pace bowler you will be able to see your progress at the end of the season with regards to ball release speed, abdominal muscle thickness, lumbo-pelvic movement control, balance and proprioception. The video recordings of your bowling action will be given to you so that you and your coach can refer to it where needed.

Will information be handled as confidential?

To ensure confidentiality of participants, each bowler will be assigned a study number. The key to the study numbers assigned is to be kept in the possession of the researcher only. Names of participants are only to be written on the consent form and not on the questionnaire. Additionally, consent forms are to be kept separately from the questionnaires. All information will be confidential and will be used only for the purpose intended in this study.

For more information, or if you have any queries, please phone me on 082 332 5776. Should you have any ethics related equiries or concerns you can phone the Human Research Ethics Committee of the University of the Witwatersrand at 011 717 1234.

If you are willing to participate in this study, please complete and sign the consent form attached.

Yours truly



Benita Olivier
PHYSIOTHERAPIST & RESEARCHER

Sequence of tests that will be done once at the start of the season and once at the end of the season:

Completion of a questionnaire	
Warm up	General warm up the way players usually do (+-10min) Bowl practice balls
Video capturing and ball speed	Bowl 6 accurate, match pace deliveries
Low back or knee repositioning	Position lumbar spine/knee in specified positions in standing
Ultrasound	Ultrasound measurements of abdominal muscles while lying on your back
Balance	Leg length measured with tape measure Star excursion balance test: reach out to touch specified points with feet
Lumbo-pelvic movement control tests	These are tests that will be done in standing, sitting, four point kneeling, lying on your back and lying on your stomach. The aim of these tests is to observe the control of movement.

Bowlers will be contacted monthly during the season - should a bowler sustain an injury, an post-injury questionnaire will be completed

Informed consent form (General): Pace Bowler

Please complete and sign this form and return to the researcher (Benita Olivier).

I_____ hereby agree to participate in this study as described to me in the information sheet. By signing this form I am agreeing to complete the questionnaires, participate in the physical test and bowling speed determination.

I understand that there are no monetary rewards for my participation and that I am not obliged to take part and can withdraw from the study at any given time.

Signature _____ Witness _____

Date _____

Informed consent form (video capturing and analysis): Pace Bowler

I_____ hereby agree to participate in the study as described to me in the information sheet. By signing this form I am agreeing to participate in the video capturing and the analysis of my bowling action.

I understand that there are no monetary rewards for my participation and that I am not obliged to take part and can withdraw from the study at any given time.

Signature _____ Witness _____

Date _____

Appendix 6 – Ethical Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
Division of the Deputy Registrar (Research)

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
R14/49 Mrs Benita Olivier

CLEARANCE CERTIFICATE	**M10430**
PROJECT	Injury Prevention Guidelines for Cricket Bowlers Based on Biomedical, Physical and Performance Factors
INVESTIGATORS	Mrs Benita Olivier.
DEPARTMENT	Department of Physiotherapy
DATE CONSIDERED	30/04/2010
DECISION OF THE COMMITTEE*	Approved unconditionally

Unless otherwise specified this ethical clearance is valid for 5 years and may be renewed upon application.

DATE 24/05/2010 **CHAIRPERSON** .....
(Professor PE Cleaton-Jones)

*Guidelines for written 'informed consent' attached where applicable
cc: Supervisor : Prof A Stewart

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University.
I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to a completion of a yearly progress report.**

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES...

Appendix 7 – Review Status of Papers Emanating from this Thesis

Paper Title	**Review Status as on 20 June 2013**
Paper 1 (Chapter 2): Static and Dynamic Balance Ability, Lumbo-Pelvic Movement Control and Injury Incidence in Cricket Pace Bowlers.	In press *Journal of Science and Medicine in Sport*
Paper 2 (Chapter 3): Injury and Lumbar Reposition Sense in Cricket Pace Bowlers in Neutral and Pace Bowling Specific Body Positions.	In press *The Spine Journal*
Paper 3 (Chapter 4): Spinal and Knee Kinematics in Low Back and Lower Limb Injury in Cricket Pace Bowlers.	Under review *Journal of Science and Medicine in Sport*
Paper 4 (Chapter 5): Cricket Pace Bowling: A Longitudinal Study of Spinal and Knee Kinematics, Ball Release Speed and Bowling Accuracy.	Under review *Journal of Science and Medicine in Sport*
Paper 5 (Chapter 6): Knee Joint Position Sense does not Correlate with Front Knee Angles or Ball Release Speed in Cricket Pace Bowlers.	In press *Gazzetta Medica Italiana.*
Paper 6 (Chapter 7): **S**ide to Side Asymmetry in Absolute and Relative Muscle Thickness of the Lateral Abdominal Wall in Cricket Pace Bowlers.	Published *South African Journal of Sports Medicine*