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The functional movement screen and abdominal muscle activation in the prediction of injuries in high school cricket pace bowlers

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The Functional Movement Screen and Abdominal Muscle Activation In The Prediction Of Injuries In High School Cricket Pace Bowlers

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A dissertation submitted to the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Physiotherapy

Johannesburg, 2017

DECLARATION

I, Candice Martin, declare that this research report is my own work. It is being submitted for the degree of Master of Science in Physiotherapy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at this or any other university.



Candice Martin

Signed on

17 MAY 2017

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UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

FACULTY OF HEALTH SCIENCES

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SENATE PLAGIARISM POLICY: APPENDIX ONE

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DEDICATION

To the Lord for unlimited grace, guidance and unlimited blessings.

To my parents for their unconditional love and support.

ABSTRACT

This research makes a meaningful contribution to the development of effective injury prevention strategies among adolescent cricket pace bowlers. This dissertation, specifically investigated two screening procedures, the Functional Movement Screen (FMS) and ultrasound measured abdominal wall muscle thickness, both of which aim to predict injury among the general and sporting population. More specifically, the dissertation investigated the applicability of these screening procedures to adolescent cricket pace bowlers.

Adolescent pace bowlers are prone to injury due to the high load and complex nature of the bowling action as well the risk factors associated with the adolescent growth spurt. Studies related to the validity of the FMS in terms of the prediction of injuries among various sporting disciplines have been conducted but none among cricket pace bowlers. Studies related to the association between abdominal wall muscle morphometry (i.e. thickness at rest and during the performance of abdominal drawing in manoeuvre (ADIM), as measured by ultrasound imaging (USI), and injury among professional and amateur cricket pace bowlers have had conflicting results and limited research related to abdominal muscle morphometry among the adolescent pace bowlers exist.

Adolescent pace bowlers that were injury free at the start of the season were recruited for this study. Details related to the nature of past injuries as well as injuries sustained during the season were monitored and recorded over a three month period.

Included in this dissertation are three original papers. The first two investigated the association between prospective in-season injury and the two above mentioned screening procedures. The third investigated the concurrent validity of FMS overhead deep squat (DS) when observer rating was compared to kinematic analysis.

The first paper (Chapter 4) investigated the association between muscle morphometry of transverse abdominis (TA), internal oblique (IO) and external oblique (EO), as measured by USI, at the start of the season and in-season injury. Results indicated that non-dominant internal oblique is thicker than dominant IO ($p=0.01$, effect size (ES) $=0.65$) in injury free pace bowlers but that non-dominant and dominant internal oblique ($p=0.47$; $ES=0.24$) is symmetrical in injured pace bowlers. Based on these findings we concluded that asymmetry in IO thickness may play a protective role against injury rather than being a predisposing risk factor to injury.

The second paper (Chapter 5) investigated the association between pre-season total FMS score and in-season injury among adolescent pace bowlers. Results indicated that there was no significant difference in total pre-season FMS scores of bowlers that sustained injuries during the season and those that remained injury free ($p=0.58$). Also, a total FMS score of 14 (the score previously found to be an accurate cut-off score) does not provide the sensitivity needed to assess injury risk among adolescent pace bowlers. It was therefore concluded that the FMS was not associated with in-season injury among

adolescent pace bowlers and that the usefulness of this tool in the prediction of injuries among these cricketers is doubtful

Paper 3 (Chapter 7) investigated the concurrent validity of the overhead DS included in the FMS when observer rating is compared to kinematic analyses. The FMS attempts to systematically score the quality of movements, among other the DS, based on specific criteria. The developers of the FMS suggest that specific mechanics related to the DS differ between levels of scoring. There were significant differences in the degree to which the torso was flexed forward, away from the vertical ($p=0.03$), where groups 3 and 2 (i.e. those participants who scored a rating of 3 and 2 respectively for the performance of the DS) remained more upright compared to Group 1. There was also a significant difference in the degree to which the femur passed the horizontal line ($p=0.05$) between the three groups. At the point of deepest descent, the femurs of Groups 3 and 2 were below the horizontal while that of Group 1 remained above. The findings of this part of the study suggest that, while raters correctly identified differences in biomechanics between groups for two of the scoring criteria (femur below horizontal and feet remaining flat on floor or board) , they did not rate the groups correctly for the remaining criteria. The concurrent validity of the observer rating of the FMS DS is therefore questionable.

In conclusion, the high load nature and complexity of the pace bowling action together with the intrinsic risk factors related to the adolescent growth spurt, expose school boy cricket pace bowlers to injury. The ability of these screening procedures to accurately identify individuals at risk of sustaining injuries are therefore of the utmost importance. Despite the popularity of the FMS, the concurrent validity of this screening tool and its lack of association with in-

season injury among adolescent pace bowlers brings the use of FMS into question. Symmetry, not asymmetry, of the IO and under-, not over-activation of the dominant TA muscles were associated with in-season injuries among pace bowlers. All of the above conflicting findings pose uncertainty regarding the applicability of these screening procedures to injury prediction among adolescent cricket pace bowlers.

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TABLE OF CONTENT

DECLARATION i

DECLARATION OF PLAGIARISM ii

DEDICATION iii

ABSTRACT iv

ACKNOWLEDGEMENTS viii

TABLE OF CONTENT ix

LIST OF TABLES xiv

LIST OF FIGURES xvi

LIST OF APPENDICES xvii

LIST OF ABBREVIATIONS xviii

OPERATIONAL DEFINITIONS xix

JOURNAL SUBMISSIONS EMANATING FROM THE WORK PRESENTED IN THIS DISSERTATION xxi

CONFERENCE PRESENTATIONS EMANATING FROM THE WORK PRESENTED IN THIS DISSERTATION xxii

CONTRIBUTIONS OF AUTHORS TO THE PROJECT xxiii

DETAILS OF AUTHORS WHO CONTRIBUTED TO THE PROJECT xxiv

1. BACKGROUND 1

1.1. Introduction 1

1.1 Problem statement 3

1.2 Research questions 3

1.3 Aim and objectives of the study 4

1.4 Significance of the study 4

2 LITERATURE REVIEW 6

2.1 Prevalence and nature of cricket related injuries among adolescents 6

2.2 Definition of Injury 7
2.3 Risk factors and injuries related to the adolescent growth spurt 11
2.4 The pace bowling action 11
2.5 Risk factors for sustaining pace bowling injuries 13
2.6 Current injury prevention strategies among adolescent cricketers 15
2.7 Relationship between core stability and injury risk 16
2.8 Methods of assessing lateral abdominal musculature 16
2.8.1 Assessment of lateral abdominal muscle morphometry using Electromyography (EMG) and magnetic resonance imaging (MRI) 17
2.8.2 Assessment of lateral abdominal wall musculature morphometry using USI 18
2.8.2.1 Reliability of USI 18
2.8.2.2 Validity of USI 18
2.8.2.3 Modifiability of USI outcomes 19
2.9 Relationship between the Functional Movement Screen and injury risk 19
2.9.1 Background and basic principles of the Functional Movement Screen 19
2.9.2 Reliability of the FMS 20
2.9.3 Predictive validity of the FMS 20
2.9.3.1 Association between total FMS score and injury risk 20
2.9.3.2 Association between total FMS score and athletic performance 21
2.9.4 Modifiability of the FMS 21
3 METHODOLOGY 24
3.1 Introduction 24
3.2 Study design 24
3.3 Study Participants 24
3.3.1 Sample size and selection 24

3.3.2 Inclusion criteria and rationale 26
3.4 Setting 27
3.5 Instrumentation and data collection 28
3.5.1 Standard FMS score sheets 28
3.5.2 DP-6600 Digital ultrasonic imaging system® 28
3.5.3 OptiTrack® optical motion capture system 28
3.5.4 Self-administered questionnaires 29
3.6 Data collection procedures 29
3.6.1 Ethical clearance 29
3.6.2 Pilot study 30
3.6.2.1 Objectives of the pilot study 30
3.6.2.2 Methods of the pilot study 31
3.6.2.3 Results from the pilot study 32
3.6.3 Main study 35
3.6.3.1 Session 1: Two weeks prior to the start of the cricket season 35
3.6.3.2 Session 2: Completion of pre-season standard questionnaire, USI measurements and FMS evaluations 36
3.6.3.3 Session 3 and 4: Completion of monthly surveillance questionnaires 38
3.6.3.4 Session 5: Completion of the post-season questionnaires 38
3.7 Statistical analyses 38
4 PAPER 1: ASYMMETRICAL ABDOMINAL MUSCLE MORPHOMETRY IS PRESENT IN INJURY-FREE ADOLESCENT CRICKET PACE BOWLERS: A PROSPECTIVE OBSERVATIONAL STUDY 39
4.1 Original article 40
4.2 Linking notes for Chapters 1,2,4 and 5 59
5 PAPER 2: THE FUNCTIONAL MOVEMENT SCREEN IN THE PREDICTION OF INJURY IN ADOLESCENT CRICKET PACE BOWLERS: AN OBSERVATIONAL STUDY 60

5.1 Original paper 61

5.2 Linking notes for Chapters 1, 2, 4,5 and 6 80

6 PAPER 3: VALIDITY OF THE FUNCTIONAL MOVEMENT SCREEN DEEP SQUAT: OBSERVER RATING VS KINEMATIC ANALYSES 81

6.1 Original article 82

6.2 Additional notes for Chapter 6 104

6.3 Linking notes for Chapter 6 104

7 RESULTS 106

7.1 Introduction 106

7.2 Injury Incidence surveillance 106

7.2.1 Pre-season surveillance 106

7.2.2 In-season injury surveillance 108

7.2.3 Post- season injuries 110

8 DISCUSSION 111

8.1 Pre- and in-season injury incidence among adolescent pace bowlers 112

8.2 Screening tools for predicting contact and non-contact injuries 114

8.3 The use of valid, reliable and user-friendly tests 115

8.3.1 The validity, reliability and user-friendliness of USI 115

8.3.2 The validity, reliability and user-friendliness of the FMS 116

8.3.3 The use of FMS screening in conjunction with other screening procedures in the prediction of injuries 119

8.3.4 The use of FMS in the prediction of contact injuries 119

9 CONCLUSION 121

9.1 STRENGTH OF THE STUDY 122

9.2 LIMITATIONS 123

9.3 RECOMMENDATIONS 123

9.3.1 Future research recommendations 123

9.3.2 Clinical recommendations 124

10 REFERENCES.....126

LIST OF TABLES

TABLE 2-1: RESEARCH RELATED TO THE ASSOCIATION OF TOTAL FMS SCORE AND INJURY RISK 22

TABLE 3-1: INCLUSION CRITERIA AND RATIONAL 26

TABLE 3-2: EXCLUSION CRITERIA AND RATIONALE 27

TABLE 3-3:INTERCLASS CORRELATION COEFFICIENT (ICC) AND 95% CONFIDENCE INTERVAL (CI) FOR RESTING, ACTIVATED AND ACTIVATED % CHANGE FOR THE USI MEASURED MUSCLE THICKNESS OF TA, EO AND IO MUSCLES DURING ADIM. 34

TABLE 4-1:DEMOGRAPHIC INFORMATION: INJURED VS NON-INJURED GROUPS AND CONTACT VS NON-CONTACT INJURIES (N=28). 49

TABLE 4-2: BODY REGIONS WHERE INJURY OCCURRED 50

TABLE 4-3:NON-DOMINANT VS DOMINANT THICKNESS AT REST AND ADIM PERCENTAGE CHANGE FOR THE WHOLE GROUP AND FOR THE BOWLERS WHO DID NOT SUSTAIN AN INJURY DURING THE SEASON (NON-INJURED BOWLERS). 51

TABLE 4-4:NON-DOMINANT VS DOMINANT THICKNESS AT REST AND ADIM PERCENTAGE CHANGE FOR INJURED AND NON-INJURED BOWLERS. 52

TABLE 4-5:THICKNESS AT REST AND ADIM PERCENTAGE CHANGE FOR INJURED VS NON-INJURED GROUP, BOWLERS WHO SUSTAINED CONTACT INJURIES VS NON-INJURED BOWLERS AND BOWLERS WHO SUSTAINED NON-CONTACT INJURIES VS NON-INJURED BOWLERS. 53

TABLE 5-1:DEMOGRAPHIC INFORMATION OF THE INJURED AND NON-INJURED GROUPS OF PACE BOWLERS 69

TABLE 5-2:BODY REGIONS WHERE IN-SEASON INJURIES OCCURRED 71

TABLE 5-3:COMPOSITE AND TOTAL FMS SCORES FOR INJURED GROUP, NON-INJURED GROUP AND ENTIRE GROUP. 72

TABLE 5-4:2X2 CONTINGENCY TABLE FOR INJURED AND NON-INJURED PLAYERS THAT SCORED ≤14 AND >14 74

TABLE 6-1:CRITERIA AND STANDARDISED INSTRUCTIONS FOR OVERHEAD DS PERFORMANCE ON THE FMS 89

TABLE 6-2:RATIONALE FOR MEASUREMENTS USED IN THE QUANTIFICATION OF EACH OF THE CRITERIA OF THE FMS DS..... 92

TABLE 6-3:DEMOGRAPHIC AND ANTHROPOMETRIC COMPARISONS BETWEEN GROUPS 97

TABLE 6-4:KINEMATIC MEASUREMENTS FOR QUANTIFICATION OF CRITERIA..... 98

LIST OF FIGURES

FIGURE 2-1: PHASES OF THE PACE BOWLING ACTION (REFERENCE TO A RIGHT HANDED BOWLER). 13

FIGURE 3-1: FMS EQUIPMENT 28

FIGURE 3-3: MAIN STUDY PROCEDURE 35

FIGURE 4-1 ULTRASOUND IMAGES OF LATERAL ABDOMINAL MUSCLES (A) MEASURED THICKNESS AT REST AND (B) MEASURED THICKNESS IN ADIM 47

FIGURE 5-1:FMS TESTS AND MOVEMENT ASPECTS ASSESSED BY TESTS 65

FIGURE 5-2 MAIN STUDY PROCEDURES 68

FIGURE 5-3: THE NUMBER OF PARTICIPANTS SCORING 1,2 OR 3 PER FMS MOVEMENT (N=27). 71

FIGURE 5-4: NUMBER OF INJURED (N=10) AND NON-INJURED (N=17) BOWLERS PER FMS SCORE. 73

FIGURE 5-5: FIELDER IN SQUAT POSITION AWAITING DELIVERY 78

FIGURE 6-1:ANATOMICAL LANDMARKS FOR THE PLACEMENT OF LIGHT REFLECTIVE MARKERS. 88

FIGURE 6-2:EXAMPLES OF THE FMS DS SCORING SYSTEM 90

FIGURE 6-3:JOINT MARKERS AND ANGLES USED FOR QUANTIFYING SCORING CRITERIA 91

FIGURE 7-1:PRE-SEASON NON-PARTICIPATION IN TRAINING DUE TO INJURY 107

FIGURE 7-2: PRE-SEASON NON-PARTICIPATION IN MATCHES DUE TO INJURY 108

FIGURE 8-1: RELATIONSHIP OF DS MOVEMENT DYSFUNCTION AND POOR TACKLING TECHNIQUE IN RUGBY 120

LIST OF APPENDICES

APPENDIX A: FUNCTIONAL MOVEMENT SCREEN INFORMATION SHEET 142

APPENDIX B: FMS SCORE SHEET 149

APPENDIX C:USI MEASURED LATERAL ABDOMINAL MUSCLES 150

APPENDIX D: PRE-SEASON QUESTIONNAIRE 151

APPENDIX E: MONTHLY SURVEILLANCE QUESTIONNAIRE 154

APPENDIX F: POST-SEASON QUESTIONNAIRE 157

APPENDIX G: ETHICAL CLEARANCE CERTIFICATE 158

APPENDIX H: GAUTENG DEPARTMENT OF EDUCATION (GDE) APPROVAL LETTER 159

APPENDIX I: INFORMATION LEAFLET - PRINCIPALS OF SCHOOLS 160

APPENDIX J: INFORMED CONSENT PRINCIPALS OF SCHOOLS 162

APPENDIX K: INFORMATION LEAFLET - BOWLERS 163

APPENDIX L: INFORMATION LEAFLET PARENTS OF BOWLERS YOUNGER THAN 18 165

APPENDIX M: INFORMED CONSENT - PARENTS OF BOWLERS 167

APPENDIX N: INFORMED CONSENT/ASSENT – BOWLERS 168

APPENDIX O: INFORMED CONSENT FOR VIDEO CAPTURING - PARENTS OF BOWLERS YOUNGER THAN 18 169

APPENDIX P: INFORMED CONSENT/ASSENT FOR VIDEO CAPTURING - BOWLERS . 170

APPENDIX Q: TURNITIN REPORT 171

LIST OF ABBREVIATIONS

ADIM – abdominal drawing in manoeuvre

DS – Deep squat

EO – External oblique

FMS – Functional Movement Screen

SFMA – Selective Functional Movement Assessment

IO – Internal oblique

TA – Transverse abdominis

USI – Ultrasound imaging

OPERATIONAL DEFINITIONS

Abdominal draw-in manoeuvre (ADIM): An exercise used as a performance test to assess change in transverse abdominis, internal oblique and external oblique muscle thickness.[1]

Activated abdominal wall thickness: Thickness of the transverse abdominis, internal oblique and external oblique muscles respectively while performing the abdominal draw-in manoeuvre.[2]

Contact injury: Any impact /traumatic injury sustained due to collision with another player or object (e.g. ball, bat, ground).[3,4]

Core stability: The ability to control the position and motion of the trunk over the pelvis to allow optimum production, transfer and control of force and motion to the terminal segment in integrated athletic activities.[5] Core stability can be achieved by the co-contraction of the muscle of the abdominal wall.[2] and the abdominal drawing-in manoeuvre has been shown to activate the lateral abdominal muscles.[6]

Extrinsic risk factors: Environmental risk factors or variables that cannot be controlled by an athlete to prevent injury.[7]

Functional movement patterns: Integrated basic movement patterns with an adequate balance of mobility and stability that allows for more complex movements to occur.[8]

Functional Movement Screen (FMS): A screening tool that specifically assesses the quality of fundamental movement patterns, in order to identify an individual's limitations and asymmetries.[8]

Injury: Damage or harm of any body region, whilst participating in a sporting activity that resulted in loss of at least one day of training or play, or that

occurred during a sporting activity that required medical attention (emergency, physiotherapy, etc.).[9]

Intrinsic risk factors: Person related risk factors that can be controlled by an athlete to prevent injury.[7]

Kinematic movement analyses: A process whereby motion of a body or system of bodies is analysed.[10]

Lateral abdominal wall musculature: Muscles that make up the lateral abdominal wall i.e. Transverse abdominis, Internal oblique, External oblique.

Non-contact injury: All injuries sustained in a manner not involving contact (e.g. overuse injuries).[11]

Pace bowlers: Bowlers classified as medium, medium-fast or fast bowlers bowling at a speed of >100km/h at high school level or >120km/h at professional level.[12]

Resting abdominal wall thickness: Thickness of the transverse abdominis, internal oblique and external oblique muscles respectively when in a non-contracted state.[13]

Ultrasound imaging (USI): A non-invasive technique used to measure size and symmetry of, among others, lateral abdominal wall musculature.[14]

JOURNAL SUBMISSIONS EMANATING FROM THE WORK PRESENTED IN THIS DISSERTATION

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CONTRIBUTIONS OF AUTHORS TO THE PROJECT

As part of the declaration of this dissertation, 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, Benita Olivier [a] and Natalie Benjamin.[a]

Kinematic data collection and the development of the calibration frame, initial camera mounting by Andrew Green, [b] Benita Olivier [a] and myself.

Drafting of written work, including the literature review and manuscripts (first and final drafts) were my responsibility. All authors have reviewed the drafts before they were submitted for publication.

Original algorithms for the kinematic aspects of this dissertation were written by Andrew Green.[b]

Herman Schoeman [c] advised on statistical analysis of the manuscripts entitled: “Asymmetrical Abdominal Muscle Morphometry is Present in Injury-Free Adolescent Cricket Pace Bowlers: A Prospective Observational Study” and “The Functional Movement Screen in the prediction of injury in adolescent cricket pace bowlers: an observational study”. Statistical analysis of all other manuscripts was performed in conjunction with Andrew Green [b] and Benita Olivier.[a]

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CHAPTER 1

1. BACKGROUND

1.1. Introduction

According to the International Cricket Council (ICC), as of 16/11/2016, the South African male cricket team is internationally ranked in the top five teams in all three formats (test, one day and T20) of the game. This may be one of the reasons cricket remains a popular sport played by many adolescent school boys in South Africa. The increase in participation of school boys in sport such as cricket, has resulted in an increase in reported injury rates among these groups.[15]

In order to transcend to provincial and national levels, the correct physical foundations should be laid at school boy level.[16] It is also important that the "prevention is better than cure" principle is taught to all parties involved in the development and management of these players.[16] To ensure that young players remain injury free for as long as possible, coaches, administrators and conditioning staff should identify risk factors and develop preventive strategies.[15]

Many intrinsic risk factors for sustaining an injury have been identified and researched. These include body composition, muscle flexibility and strength, ligament laxity and faulty foot biomechanics.[8] Decreased core strength also contributes to back and extremity injuries.[17] Injury risk is however multi-factorial and the evaluation of these risk factors individually does not take into consideration how functional movement patterns required for sport are performed.

The Functional Movement Screen (FMS) has been developed as a pre-participation screening procedure to assess the quality of any athlete's fundamental movement patterns and establish the athlete's risk for sustaining an injury.[8] The reliability and predictive validity of the FMS in many different sports and occupations have been well researched and deemed high. After conducting an extensive literature search, no literature documenting the predictive and

concurrent validity of the FMS in predicting injuries among high school cricket pace bowlers could be found. Also, the concurrent validity of the FMS i.e. comparison between real-time observer rating compared to kinematic analyses of biomechanics during the performance of the movements included in the FMS, has yet to be researched thoroughly.

Decreased core stability has been identified as a risk factor for sustaining injuries.[17] Peate et al.(2007)[17] found a clear correlation between trunk muscle activity and extremity movement and also found that core stability is also challenged by functional movement methods. A stable core allows an athlete to control the position and motion of the trunk over the pelvis thereby allowing production, transfer and control of force and motion to distal segments when complex, integrated athletic activities are performed.[5] Core stability can be achieved by co-contraction of the lateral abdominal wall muscles, as is done in the performance of abdominal drawing in maneuvers (ADIM).[6]

Recently, ultrasound imaging (USI) has been used to measure abdominal muscle activation and quantify muscle morphology and behaviour.[18] It has been validated as a means of measuring the size and symmetry of various muscles by comparing to magnetic resonance imaging (MRI) and has validity as an indicator of muscle activation with indwelling electromyography (EMG).[18] This method was therefore considered valid for measuring the resting and activated abdominal muscle thickness of the various high school cricket pace bowlers.

Considering the above, the researcher hypothesised that an association between core stability, FMS performance and injury risk existed. This study therefore aims to determine if the FMS and abdominal wall muscle activation are valid methods for predicting injuries among high school cricket pace bowlers. A secondary aim of this study was to determine the concurrent validity of the FMS deep squat (DS) when observer score is compared to kinematic joint analyses.

1.1 Problem statement

Firstly, musculoskeletal screening processes for cricket players exist and have evolved over the years. The screening procedure currently being implemented by all South African provincial unions, contains a large number of tests making the procedure time consuming. Furthermore, the predictive validity of the individual tests included as well as the current screening procedure as a whole, have not been researched. The FMS only includes seven functional movement tests and three screening tests, while measurement of lateral abdominal wall thickness using USI by a trained professional only takes several minutes. These aspects make these tools more practical and less time consuming. Also, USI screening equipment or single USI screening test might be more costly than some of the current screening methods, the immediate and future cost of healthcare related to injury could far exceed that of a preventative USI screening test. Although studies have confirmed the reliability of the FMS as well as lateral abdominal wall thickness and symmetry, the validity of these tools to predict injuries among cricket pace bowlers is still to be confirmed.

Secondly, even though the developers of the FMS[19] have set out specific scoring criteria for each movement included in the FMS, it remains an observational screening procedure. There is therefore still a strong subjective component which may influence the outcome and validity of the screening procedure. For this reason, it is important to explore the concurrent validity of the FMS.

1.2 Research questions

Following the above statements, the research sought to answer the following questions:

1. Is abdominal muscle thickness/activation as measured by USI associated with in-season injury among high school cricket pace bowlers?
2. Is the FMS total score associated with in-season injury among high school cricket pace bowlers?

3. What is the concurrent validity of observer rating versus objective kinematic motion analysis of the DS FMS test?

1.3 Aim and objectives of the study

The first aim of this study was to determine whether pre-season abdominal muscle thickness/activation and total FMS is associated with in-season injury among cricket pace bowlers. The second aim of this study was to compare real-time observer rating of the FMS deep squat (DS) screening to objective kinematic motion analysis of the FMS DS test

The objectives of this study are to:

1. determine if USI measured lateral abdominal wall thickness is associated with in-season injury.
2. determine if pre-season FMS scores are associated with in-season injury
3. determine the concurrent validity between FMS DS scores obtained by comparing kinematic analysis and visual observation;

1.4 Significance of the study

The ethical considerations of a screening tool should be taken into account as it is not a diagnostic tool, but used for detecting individuals who are at risk of injury. These tools are therefore used to tell seemingly injury free or healthy individuals that something "might" be wrong or is placing them at risk of sustaining an injury. Confirming the validity of these tests are therefore of the utmost importance.

Establishing an association between lateral abdominal wall activation and/ or FMS and potential in-season injuries, will enable health and fitness professionals to identify those players potentially at risk of sustaining in-season injuries. In an attempt to prevent injury, a prevention programme can be prescribed for these bowlers. Further research should investigate if rehabilitation or training of the abdominal muscles and correction of functional movement patterns will prevent injury.

In addition, if the association between these tests and in-season injury is high, health and conditioning professionals should consider implementing them in a clinical setting as the procedures are more user-friendly and time efficient than the procedures that are currently used.

Lastly, by confirming the concurrent validity of FMS DS by comparing kinematic variables to visual observation scores, it can be established if subjective visual observation can judge the functional movements with sufficient accuracy.

CHAPTER 2

2 LITERATURE REVIEW

The game of cricket consists of three unique aspects: batting, bowling and fielding, all of which are associated with injury risk.[16] Cricketers require high levels of fitness and technical skill to perform these unique aspects, leaving them more susceptible to overuse injuries because of repetitive training.[20] This literature review focuses on general aspects related to the prevalence and nature of cricket related injuries among adolescents. It also describes the intrinsic and extrinsic risk factors related to cricket as well as risk factors related to the adolescent growth spurt. The relationship between efficient abdominal wall muscle activation and the quality of functional movement skills is also discussed. Literature specifically related to each paper is set out in the chapters dedicated to each paper specifically.

This literature review was done under the following subheadings:

2.1 Prevalence and nature of cricket related injuries among adolescents
2.2 Definition of Injury
2.3 Risk factors related to the adolescent growth spurt
2.4 The pace bowling action
2.5 Risk factors for sustaining fast/pace bowling injuries
2.6 Relationship between core stability and injury risk
2.7 Methods of assessing lateral abdominal wall musculature
2.8 Relationship between functional movement and injury risk
2.9 The Functional Movement Screen
2.10 Current injury prevention strategies among adolescent cricketers

2.1 Prevalence and nature of cricket related injuries among adolescents

Both international[21] and local[22] studies have researched the prevalence and nature of injuries sustained by adult and adolescent cricket players. Long term adult cricket injury surveillance studies that have been conducted found that

bowlers were at greatest risk of sustaining injuries (40-45%), followed by fielders (25-33%) and then batsmen (17-21%).[22] The majority of these injuries were sustained during matches (52%-58%) played in the early part of the season (35%).[22] Of these injuries 45-49% were in the lower limb, 18-23% in the back and trunk and 23-29% upper limb injuries.[22]

The high injury incidence among cricket pace bowlers is mainly due to the high-load nature of the pace bowling action which constitutes a complex sequence of forceful actions.[23] Although injury surveillance among adult cricketers has been well documented, limited research exists regarding injuries among high school cricket players. Seasonal injury incidence rates among school boy cricketers correlated with previous studies on club and provincial cricketers.[22] Similar to the adult player injury incidence rate mentioned above, bowlers (47%) were at greatest risk of sustaining injuries, followed by batsmen (30%) and fielders (23%). Injuries occurred equally during matches (46%) and training (47%). Among these adolescent players, trunk and back injuries (33%) were most prevalent, followed by upper limb injuries (25%) and lower limb injuries (23%).[22]

Similar to findings of Stretch et al.,[22] a retrospective study established that during the 2003/2004 cricket season 34.2%, of 196 elite South African school boy cricketers' sustained injuries.[24] Furthermore, the majority (50.9%) of these injuries were sustained during fast bowling. Considering the above findings it is clear that young South African fast bowlers of all ages (including U15 - U18) remain at great risk of injury. It is therefore recommended that in an attempt to decrease these injury incidence rates, cricket health care providers, administrators and coaches identify risk factors and implement injury prevention programs.[15]

2.2 Definition of Injury

The lack of clear definitions of the term injury and sub-classifications of contact and non-contact injures poses methodologic limitations in the current literature.[11] Variations in definitions can create inconsistencies in reporting of data and make

inter-study comparisons difficult.[25] To enable the comparison of injury statistics in international cricket injury surveillance studies, a consensus statement defined an injury as: “any significant 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”.[3] Although this definition was retained in a 2016 concensus,[4] it was not the only recommended definition. Revisions was required as the 2005 consensus definition only contained detail on the inability to participate in matches. Non-participation in training could keep a player from developing, promoting and practicing basic athletic and sport-specific skills required for participating and performing in his chosen sport. Non-participation in training could therefore not only hinder the athlete’s performance but also increase risk of injury. As a result, the 2016 consensus proposed “match-loss injury” as an alternate term for the previously named “significant injury”.

As the studies included in this dissertation focused on screening procedures related to injury risk, an injury definition which included non-participation in both matches and training was required. The National Athletic Association Injury Surveillance system [26] as well as a study aiming to identify injury among soccer players [27] included physical conditions or complaints in both matches and training sessions in the respective injury definitions. The 2016 consensus therefore constructed the term “general time-loss injury” for any injury (or illness) that, as oppose to a “match-loss injury”, cause a player to be unavailable at all general times for example on training days, off days and in the off-season.

The definitions of injury in the 2005 consensus paper[3] as well as that of Engebretsen et al. (2010)[27] included all physical complaints and medical conditions and not only those related to the musculoskeletal system. Neither the FMS nor the lateral abdominal wall thickness is related to medical illness. For the purposes of this dissertation the inclusion of medical illness in the definition of injury would therefore not be appropriate. Like Roussel et al. (2011)[28] who investigated injury incidence among dancers, the definition of injury in this dissertation only include physical damage to a musculoskeletal structure.

Considering all of the above, for the purposes of this dissertation, an injury was defined as musculoskeletal damage or harm to any body region, sustained while participating in a sporting activity, that resulted in loss of at least one day of training or play OR that occurred during a sporting activity that required medical attention (e.g. emergency, physiotherapy). This definition is similar to that of Olivier et al. (2013)[9] who also investigated intrinsic risk factors among pace bowlers.

An injury was not limited to specific joints but included any injury along the various kinetic chains during the performance of the functional movements. The FMS specifically analyses and predicts injuries within movement patterns and not isolated joint specific movements.[19] Furthermore, dysfunction, limitation or asymmetry in any joint along the kinetic chain will compromise another and the movement pattern as a whole. As previously mentioned the muscles of the abdominal wall form part of the core which has an unequivocal role in the effectiveness with which limbs are moved during the performance of complex athletic movements. For these reasons injuries of the upper limb, lower limb, back and trunk were included in the definition of an injury and applicable to both papers 1 and 2.

From the injury definition used in this dissertation, it is also clear that both contact and non-contact injuries were investigated. When a pre-participation screening tool is developed it is of the utmost importance to consider all the sport-specific demands placed upon the athlete as well as any possible mechanisms of injury (contact or non-contact) to which the athlete could be exposed. One must bear in mind that bowlers are also required to bat and field and are therefore also exposed to contact injuries by collision with another player, the ball, ground, boundary rope or wickets while fielding or batting.[24]

It is assumed that contact injuries are less likely to be affected by muscle morphometry or functional movement patterns, unless movement patterns can help avoid contact. In cricket, measures to address contact injuries, such as those caused by collision with the ball, are primarily extrinsic forms of protection such as helmets and padding.[29] However, these are only worn by batsmen and fielders

in certain positions (wicketkeeper and silly point), while bowling or fielding cricketers do not wear any protective gear and therefore have to rely on the appropriate structural integrity of the body, athletic ability and the correct technique in order to avoid or lessen impact caused by contact with the ball or ground.[29] The core muscles control both position and motion of distal body segments during integrated athletics activities [5] and improve performance and skill.[30] In addition to enhanced athletic performance, a stronger core also allows for greater structural integrity of the body wall. Structural integrity is important in instances where there may be a collision between two bodies as structural damage is inversely related to structural integrity. It was thus deemed appropriate to include both contact and non-contact injuries in the definition of injury for both papers 1 and 2.

In an attempt to standardise the definition for non-contact anterior cruciate ligament (ACL) injuries, Marshall (2010)[11] proposed the following: “An injury sustained by an athlete without extrinsic contact by another player or object on the field.” Similarly, Walden et al. (2015)[31] defined non-contact ACL injuries as “an injury occurring with no bodily contact with another player”. A 2016 consensus[4] suggested that the mode of onset should be considered for non-contact injuries and distinguished between “sudden-onset” (e.g. ankle sprain during bowling run-up) and “gradual-onset” (e.g. low back pain with gradual onset which is experienced during and aggravated by the fast bowling action). From these definitions it is clear that the damaged body region was not struck directly with force. As cricketers are exposed to not only contact with another player but also other inanimate objects (including ground, ball and boundary rope) Marshall’s 2010 [11] definition is more applicable to this dissertation. A non-contact injury was therefore defined as any injury sustained in a manner not involving contact (e.g. overuse injuries).

Orchard et al. (2005,2016)[3,4] and The National Athletic Association Injury Surveillance system [26] defines a contact injury as an injury that occurs due to a field impact or contact with objects, surfaces or other players. For the purposes of the studies included in this dissertation a contact injury was similarly defined as any injury sustained due to collision with another player or object (e.g. ball,

bat, ground).

2.3 Risk factors and injuries related to the adolescent growth spurt

The adolescent athlete may be particularly vulnerable to sport injury due to the physical and physiological processes related to growth. Muscle tendon tightness, decreased physical strength and non-linearity of growth is associated with the adolescent growth spurt.[32] Some adolescents might also be at increased risk due to immature or underdeveloped coordination, skills and proprioception, factors that together with muscle strength, range of motion, timing and reactive ability influence athletic ability.[33]

Due to differences in the structure of growing bone in children compared to matured bone in adults, a particular mechanism of injury may result in different pathological conditions in the two groups.[34] Strong, in-coordinate muscle contractions are for example more likely to lead to an avulsion fracture at the site of the muscle tendon attachment in adolescents rather than a tear of the muscle or tendon itself as seen in adults.[34] The mechanisms with which adolescent pace bowlers sustain injuries also differ from that of adult pace bowlers. Stretch (2014)[7] found that compared to elite players, young cricketers are more susceptible to traumatic type injuries and sustain less overuse type injuries.

2.4 The pace bowling action

The game of cricket requires three distinct disciplines namely batting, bowling and fielding. Bowlers in cricket can be categorised as either spin or pace bowlers. Spin bowlers add rotation to the ball delivery, causing the ball to deviate from the original flight direction when it hits the ground.[35] Pace bowlers aim to beat the batsman by deviations in speed and direction of flight of the delivery.[35]

Bartlett et al. (1996)[36] describes four distinct phases of the pace bowling action namely run-up, pre-delivery stride, delivery stride and follow-through. A description and illustration of these phases in reference to a right handed bowler is shown in Figure 2.1. Pace bowlers are also categorised by pace bowling technique as side-on, front-on or mixed action bowlers.[37] Side-on vs front-on techniques are determined by the alignment of the two shoulders at back foot

contact and the degree of shoulder counter-rotation away from the batsman during the delivery stride.[38] The mixed action is a combination of the upper body configuration of the side-on technique and the lower body configuration of the front-on technique.[37]

During the pace bowling action, bowlers must absorb vertical and horizontal components of ground reaction forces, which are transferred from the lower limbs to the spine.[37] During front and rear foot strikes forces can be as much as five and two times body weight respectively.[23,37] Additional forces to the lumbar spine are also created by the combination of hyperextension, lateral flexion and rotation during the delivery stride.[37,36]

These biomechanical factors contribute to the aetiology of, in particular, lumbar spine injuries among pace bowlers.[39] Lumbar stress injuries, specifically pars interarticularis stress reactions and stress fractures, on the side contra-lateral to the bowling arm, are the most prevalent injury type among adult [40,41] and adolescent [42] pace bowlers. Gregory et al. (2002)[35] notes that although lower back injuries in pace bowlers have been a popular subject of published research, they found no significant difference in the incidence of lower back injuries when pace bowlers were compared to spin bowlers. They did however conclude that pace bowlers have a higher incidence of knee and ankle injuries compared to spin bowlers.

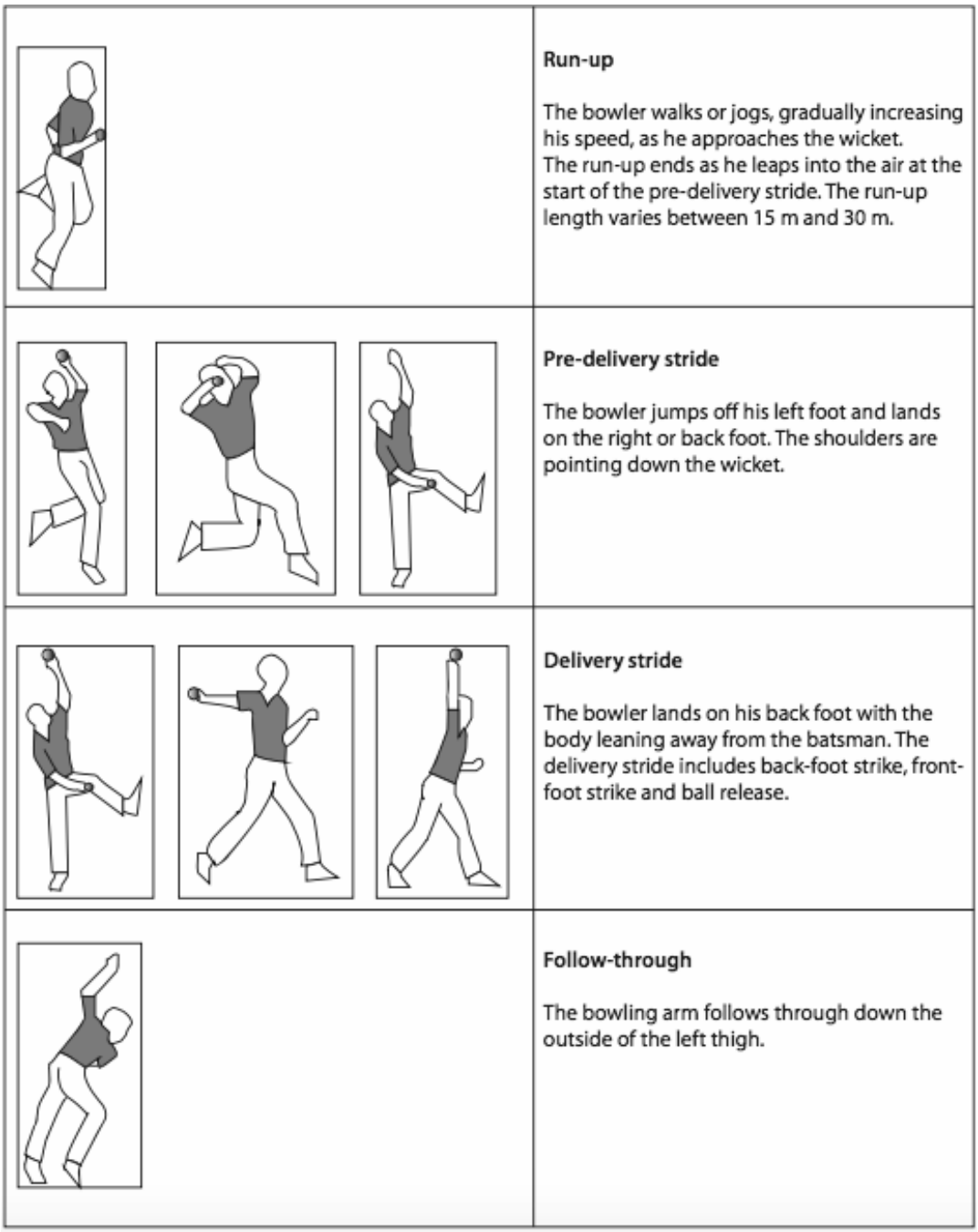


Figure 2-1: Phases of the pace bowling action (reference to a right handed bowler).[43]

2.5 Risk factors for sustaining pace bowling injuries

A combination of extrinsic and intrinsic risk factors predisposes any athlete to injury. Extrinsic or environmental risk factors, related to cricket include poor bowling action, work load and player position at the time of play.[44,45] Portus et al. (2014)[38] highlighted biomechanical risk factors related to the bowling action and found a significant association between shoulder counter rotation and lumbar

spine fractures. An association between injury and knee flexion range at front foot strike and ball release phases have also been investigated. While Portus et al. (2014)[38] found that bowlers who remained injury free had greater knee flexion during these bowling phases, Olivier et al. (2015)[46] found no significant difference in knee flexion angle between injured and non-injured bowlers. High bowling workload has been identified as a risk factor for overuse type injuries among junior fast bowlers.[47] Studies related to the workload of junior bowlers usually only consider workload specifically related to the bowling action, e.g. the amount of overs bowled during a season. It should however be kept in mind that at high school level, athletes often participate in multiple sports during the same season. The accumulated workload of the bowling action and other additional sports (especially those of unilateral rotational nature) might further increase a bowler's risk of sustaining an injury.

Intrinsic or person-related risk factors include muscle asymmetry, core stability deficiencies, postural defects and impact forces.[44] In addition poor dynamic balance and asymmetrical strength and flexibility resulting in poor fundamental movement patterns, essential for complex athletic movements such as the bowling action, have also been associated with increased risk for injury among athletes in general.[8] Other intrinsic risk factors specifically related to adolescent fast bowlers are ipsilateral (to the bowling arm) hip internal rotation of >40°, contra-lateral ankle dorsiflexion lunge of <14.0 cm and reduced hamstring flexibility.[45]

While bowlers are at highest risk of injury, it should be kept in mind that they are still required to bat and field during training and matches, which exposes them to injuries other than those associated with the pace bowling action. To ensure injury prevention and career longevity in the potential next generation elite fast bowlers, it is important to identify these risk factors and implement appropriate strategies at school boy level.[48] This study investigated intrinsic risk factors using USI and the FMS.

2.6 Current injury prevention strategies among adolescent cricketers

Prevention strategies include screening procedures to identify individuals at risk of sustaining prospective injuries as well as implementing programs aimed at addressing the identified risk factors.

Musculoskeletal screening is a clinical tool intended to identify risk factors that can be modified to reduce injury risk and is a common procedure in many sports.[49] Current cricket screening procedures include musculoskeletal tests aimed at assessing individual joints in isolation and include tests such as seated knee extension test, modified Thomas test, hip internal and external rotation tests, ankle dorsiflexion lunge, bridging hold, prone four point hold and calf heel raises.[50] The single leg squat is often included because of the association between knee kinematics during this test, pelvic femoral stability during the bowling action and low back injury incidence among adolescent fast bowlers.[51]

Results of a systematic review [52] demonstrated the beneficial effects of exercise-based injury prevention programs in youth sports. Injury prevention programs that focus on specific injuries as well as those targeting all injuries showed a significant reduction in injury incidence among adolescent athletes. In another systematic review, it was concluded that injury prevention strategies that focus on pre-season conditioning, functional training, education, balance and sport-specific skills, which should be continued throughout the sporting season, are effective in the prevention of injuries among this population.[53] Stretch and Gray (2013)[54] have developed an injury prevention programme known as SPOT for South African pace bowlers which incorporates screening, physical preparation, over- bowling and technique modification.

In cricket, protective gear such as helmets and padding are used for the primary prevention of contact injuries. However, evidence for the effectiveness of protective equipment in injury prevention is inconclusive and requires further assessment.[53]

2.7 Relationship between core stability and injury risk

The importance of optimal core function for stabilisation and force generation[5] as well as injury prevention[55] in all sports is increasingly being recognised. Core stability is essential for maximal force generation and minimal joint load in all types of activity.[5]

Core stability has been defined as “the ability of the lumbopelvic-hip complex to prevent buckling and to return to equilibrium after perturbation.”[17] Although non-contractile skeletal structures such as bones and ligaments contribute to some degree, core stability is predominantly maintained by the dynamic neuro-muscular elements.[55] The lateral abdominal muscles including the TA, IO and EO provide stability to the trunk in different functional activities and there is a clear relationship between trunk muscle activity and extremity movement. In both the above mentioned studies the authors stated that decreased core stability is a risk factor for sustaining musculoskeletal injuries and that strengthening these muscles may decrease the incidence of these injuries.[5,55] It was further stated that core stability can be tested using functional movement methods.[5,55] The researcher therefore hypothesised that those athletes who performed well in the FMS would also have good core or abdominal activation and vice versa. Thus the argument may be that the FMS is dependent on good, symmetrical lateral abdominal stabilisation/activation.

Okada et al. (2011)[56] evaluated the relationship between functional movement, core stability and performance and established that significant correlations exist between some of the functional movement patterns and core stability exercises but emphasised that both are not good predictors of performance.

2.8 Methods of assessing lateral abdominal musculature

Measurement of size of each lateral abdominal wall muscle in relation to the same, opposite side muscle or other muscles not only provides information regarding the difference in structure but also function i.e. muscle activation patterns.[57] Various methods of assessment have been researched and implemented in clinical practice. These methods of assessment include MRI and

USI.

2.8.1 Assessment of lateral abdominal muscle morphometry using Electromyography (EMG) and magnetic resonance imaging (MRI)

Surface EMG is often used in research and clinical settings to measure and compare levels of activity in both the same and different muscle during the performance of activity.[11] Drysdale et al. 2002[58] investigated the activity of the rectus abdominis (RA) and EO during the performance of ADIM and posterior pelvic tilt, while Steinlich et al. (2003)[59] investigated these muscles and rectus femoris during exercises with different training devices and a traditional crunch. Martuscello (2012)[60] conducted a systematic review to determine which type of exercise elicits the largest amplitude, measured by EMG, activity in quadratus lumborum (QL), TA and lumbar multifidi.

Surface EMG recordings can be influenced by the depth of targeted subcutaneous soft tissue which is variable depending on body composition.[61] Muscle cross-talk, where the EMG signal from one muscle interferes with that of another, challenges this technique's ability to discriminate between muscles and can therefore limit the reliability thereof.[61] While intramuscular EMG can be used for the assessment of deeper muscles, this method is more invasive and causes discomfort.[61]

MRI has been used to investigate the cross sectional area of different trunk muscles in different states of both injured and non-injured pace bowlers. These muscles include the QL,[13,62,40] Erector Spinae,[13] Multifidus,[63,64] Psoas,[13] IO[13] and TA.[13,6]

Compared to other radiological modalities, MRI has superior soft tissue resolution and multi-planar capabilities which makes this a particularly useful modality in the assessment of lateral abdominal wall musculature.[65] However this method is not cost effective and MRI equipment has limited availability usually only in hospital settings. Furthermore, MRI imaging has to be done and interpreted by highly skilled professionals. USI might be limited in its ability to fully visualise detailed pathology in relation to other structures.[65] However, due to the MRI limitations mentioned above, USI may be the preferred method for investigation of lateral

abdominal wall muscle thickness.

2.8.2 Assessment of lateral abdominal wall musculature morphometry using USI

Real-time USI has been established as a valid method in the field of rehabilitation. This method is not only used for assessment of lateral abdominal muscles but also as a clinical biofeedback tool in rehabilitation.[6,66]

2.8.2.1 Reliability of USI

A systematic review concluded that the majority of high quality studies found that USI has good intra-and inter-rater reliability (ICC>0.90).[67] The authors of this review further concluded that improved reliability was observed among studies examining muscle thickness (as opposed to other soft tissue structures) and when using mean measurement values obtained by more experienced examiners.[67] Teyen et al. (2011)[68] suggested that although reliability of experienced examiners is higher, ratings by novice raters that have been properly trained are still reliable (ICC 0.86-0.94). Koppenhaver et al. (2009)[18] found intra- and inter-rater reliability of same-day measurement to be higher than between-day measurements. Additional information related to the reliability of USI is discussed in Paper 1 (Chapter 4).

2.8.2.2 Validity of USI

Criterion-related validity

A systematic review by Koppenhaver et al. (2009)[18] found that USI, when compared to other gold standard modalities, was a valid tool for the assessment of rested and activated trunk muscle thicknesses. More specifically strong correlations (ICC 0.84-0.94) between USI and MRI measurements have been reported.[6] Hodges et al. (2003)[69] also found a strong relationship between EMG activity and change in muscle thickness from rested to activated state. Koppenhaver et al. (2009)[18] emphasized that variables such as the muscles being measured, the type of activity performed and the intensity of contraction affect the degree to which the results agree.

2.8.2.3 Modifiability of USI outcomes

While establishing the clinical reliability and validity of a screening tool is beneficial, it would have little clinical relevance if the initial outcome could not be changed by an appropriate, standardised intervention. In a group of elite cricketers Hides et al. (2008)[64] reported an increase in the cross sectional area (CSA) of multi-level multifidi muscles and a resultant decrease in lower back pain after a progressive stabilisation training programme was followed. Similarly, motor control of anterolateral abdominal muscles of the same group were improved after following the same stabilisation programme.[70] When a similar stabilization programme with unilateral weight-bearing was prescribed to elite cricketers, a normalisation of previously excessive co-contraction of abdominal muscles in response to axial loading was reported.[71]

2.9 Relationship between the Functional Movement Screen and injury risk

Although the risk for sustaining musculoskeletal injury is multi-factorial, muscular imbalances, poor neuromuscular control and core instability have increasingly been recognised as risk factors.[72,17] As previous injury has also been established as a potential risk factor,[73] Kiesl et al. (2007)[8] hypothesised that changes in motor control due to previous injury may be exposed when multiple systems are challenged simultaneously by movement. The FMS has subsequently been established as a test to assess neuromuscular impairments as a result of injury.[74]

2.9.1 Background and basic principles of the Functional Movement Screen

The FMS was designed to identify athletes who experience pain with performance of, what the developers of the FMS deemed, functional movement patterns or those who are unable to perform these patterns without compensation.[75] The FMS consists of seven sub-tests (DS, hurdle step (HS), in-line lunge (ILL), shoulder mobility test (SM), trunk stability push-up (TSPU), active straight leg raise (ASLR) and rotary stability (RS) test) and three clearing tests (See Appendix A). The developers of the FMS hypothesized that these movement patterns, place an individual in positions where functional movement

limitations and asymmetries may be identified, making it a potential predictor of injury.[75] The FMS also attempts to systematically quantify injury risk by allocating a score from zero to three, based on specific scoring criteria[76] (See Appendix A). A composite (total) score is calculated by adding the scores of the individual tests. For bilateral tests (i.e. tests where scores are allocated for performance on both the left and right sides) the lowest of the two scores is used for calculation of the total score.[19]

2.9.2 Reliability of the FMS

Numerous studies[77,78,79] have investigated the inter-rater and inter-session (test-retest) reliability of the FMS and found both to be high. Onate et al. (2012)[77] reported inter-session and inter-rater reliability (ICC, SEM) for the total FMS scores to be 0.92,0.51 and 0.98,0.25 respectively. Smith et al. (2013)[78] reported ICC values for inter-rater and intra-rater reliability of 0.87-0.89 and 0.81-0.91, respectively. Like Minick et al. (2010),[79] Smith et al. (2013)[78] also determined that, irrespective of FMS experience, inter-rater reliability remained substantial and that the intra-rater reliability was not increased with FMS certification. A systematic review found moderate evidence for acceptable intra- and inter-rater reliability levels for total FMS score when FMS performance was rated live (i.e. not from video playback).[80]

2.9.3 Predictive validity of the FMS

2.9.3.1 Association between total FMS score and injury risk

The ability of the total FMS score to identify different groups of individuals at high risk of sustaining an injury have been investigated by numerous researchers (Table 2-1). While some have found a strong association with injury risk others have not found any association. Considering the conflicting conclusions of the studies summarised in Table 2-1, it is clear that consensus regarding the predictive validity of the FMS has not been reached. Although a wide variety of different population groups (in terms of level of activity, age, gender, nationality, occupation etc.) as well as different athletes (with regards to specific sports as

well as level of participation) have been investigated, there is no evidence regarding the predictive validity of the FMS for cricket pace bowlers.

2.9.3.2 Association between total FMS score and athletic performance

Although altered movement patterns often increase the risk of injury, athletes often use these alternative movement patterns to achieve optimal performance.[46] Although primarily used as a pre-participation screening tool, the FMS is also intended to measure movement efficiency.[19] The developers of the FMS state that inefficient movement patterns can decrease athletic performance.[19] This implies that athletes with higher FMS scores would display more efficient movement patterns which would enable them to perform basic athletic tasks comparably better than athletes with low FMS scores. This ability would in turn make them better quality athletes.

2.9.4 Modifiability of the FMS

Kiesel et al. (2011)[74] investigated if an off-season intervention programme could effectively improve initial FMS scores of professional American football players. Like Goss et al. (2009),[81] who conducted a similar study on firefighters, Kiesel et al. (2011)[74] found that initial total FMS scores improved after corrective exercise intervention. It was noticeable, however, that low performance on the DS score (score of 1) was strongly associated with the lack of an individual's ability to improve overall performance. In contrast Frost et al. [82] reported that for a group of firefighters, FMS scores did not change after a twelve week intervention programme.

2.9.5 Summary

Among adolescent cricketers, pace bowlers have the highest injury risk.[83] Various outcome measures for individual fitness components (muscle strength, range, speed etc.) are used by cricket health and fitness professionals during a standard assessment. These measures are, however, done in isolation and not within the kinetic chain used during a functional movement. The efficacy of these standard

measures to predict injuries when functional movements are performed is therefore questionable. Even though the FMS has been found a reliable predictor of injury for numerous other sports,[8,72] the validity for predicting injury among cricket pace bowlers is yet to be established. Significant correlations have been found between various functional movements and core stability.[56] The purpose of this study was therefore to firstly determine if FMS and lateral abdominal thickness are good predictors of injury among cricket pace bowlers and secondly to establish the concurrent validity of FMS scoring system by comparing visual estimation with kinematic analysis.

Table 2-1: Research related to the association of total FMS score and injury risk

Research that have found an association between total FMS score and injury risk					
Author	**Population**	**N**	**Cut-off score**	**Odds ratio (CI)**	**Sensitivity (Sn)** **Specificity (Sp)**
Kiesl et al. (2007)[8]	American Football (professional)	46	≤14	11.67 (2.47-54.52)	Sn=0.54 Sp=0.91
Chorba et al. (2010)[72]	Female Collegiate Division II soccer, basketball, volleyball	38	≤14	3.85 (0.98-15.13)	Sn=0.58 Sp=0.74
O'Connor et al. (2011)[84]	Male military officers	74	14	2.0 (1.3-3.1)	Sn=0.45 Sp=0.71
Peate et al. (2007)[17]	Firefighters	433	17	n/a	n/a
Kiesl et al. (2014)[85]	American Football (professional)	238	14	Not reported	Sn=0.26 Sp=0.87
Butler et al. (2013)[86]	Firefighters	108	≤14	8.31 (3.2-21.6)	Sn=0.80 Sp=0.62
Teyhen et al. (2015)[87]	US army rangers	211	Multiple factors assessed	1.9 (1.4-2.6)	Sn=0.90 Sp=0.98
Lisman et al. (2012)[88]	Marine Corps Officer candidates	874	≤14	2.04 (1.32-3.15)	
Research that found no association between total FMS score and injury risk					
Bardenett et al. (2015)[89]	High school athletes	167	14	n/a	Sn=0.56 Sp=0.38

Dossa et al.(2014)[90]	Major Junior Hockey players (ages 16-20)	20	≤14	2.33 (0.37-14.60)	Sn=0.5 Sp=0.7
Letafatkar et al. (2014)[91]	University athletes	100	17	4.70	Sn=0.65 Sp=0.78
Warren et al. (2015)[92]	College athletes	167	≤14	1.01 (0.53-1.91)	

CHAPTER 3

3 METHODOLOGY

3.1 Introduction

This chapter describes the methodology related to the study design, participants, setting, instrumentation main study procedures and statistical analysis of the pilot and main study. A description of the specific methodology related to each paper is given in the chapters dedicated to the individual papers.

3.2 Study design

This study had a prospective, observational, quantitative design.

3.3 Study Participants

The participants were high school cricket pace bowlers. Pace bowlers are considered to be all medium and fast bowlers. At high school level, medium pace bowlers are bowlers that bowl at speeds of 100-130km/h while at professional level bowl at a speed of 120km/h or faster.[12] The target population of 243 pace bowlers was calculated as follows: 9 (cricket playing public high schools in Eastern Pretoria) X 9 (nine cricket teams per school) X 3 (average number of pace bowlers per team).

3.3.1 Sample size and selection

The sample size estimation was done with the following assumptions:

- A two-sided two-sample t-test was performed at a 5% level of significance
- The difference between the FMS mean scores for injured and uninjured bowlers were 3.0 (14 and 17)
- The standard deviation for injured bowlers was 2-3
- The standard deviation for non-injured bowlers was 2-2.5
- The sample size for injured bowlers was 10
- The sample size for non-injured bowlers was 20

Using the above numbers results in a power for the sample of 72% to 95%.

These assumptions were based on the results of the study conducted by Kiesel et al.(2007)[8] In their study, the mean score for players who sustained injuries was 14.3 (±2.3) and 17.4 (±3.1) for those who were not injured. Thirteen participants were injured while 33 were not injured resulting in an injured: not-injured ratio of 1:2.5.

A total of 30 participants was proposed for each study included in this dissertation. which corresponds with other studies involving kinematic movement analyses. These studies each had samples of between 18 [93] and 28.[76] Olivier et al.(2015)[9] included 31 amateur cricket bowlers to establish the relationship between pace bowling performance and regional spine and knee kinematics. As indicated in section 3.6.3.2 (p. 35) the kinematic recording of the FMS DS and observer rating of the different FMS movements were done simultaneously. The practicality, logistics and the number of variables (joint angle and distance measurements relative to each other) related to kinematic studies were therefore also considered when the sample size was determined.

A sample of convenience was selected. Information regarding the study was sent to nine cricket playing public high schools in Eastern Pretoria, namely: Hoërskool Menlopark, Hoërskool Waterkloof, Hoërskool Die Wilgers, Afrikaans Hoër Seuns Skool, Pretoria High School for Boys, The Glen High School, Hoërskool Garsfontein, Christian Brothers College, St. Albans College. Schools that volunteered to participate were requested to send the researcher a list of potential participants. To reach the proposed sample of 30, a computer program was used to randomly select the final participants.

On the day of the main study screening (See Figure 3-2; p 34) two participants did not attend their scheduled screening sessions due to personal and transportation problems.

For this reason, 28 participants were included in the main study of Paper 1 (Chapter 4). Another participant did not complete the FMS evaluation as he experienced 8/10 knee pain during the performance of the DS. According to the FMS guidelines,[19] when a participant experiences pain during the performance of any of the tests, the screening is ceased (See Chapter 5, p.56). Twenty-seven participants were therefore included for the purposes of Paper 2 (Chapter 5). An unavoidable limitation of kinematic movement analysis is the disappearance of on screen markers as a particular movement is executed. Disappearance of these markers precludes accurate kinematic movement analysis. Kinematic data collected from seventeen of the 27 participants that completed the FS DS was viable for kinematic movement analysis. The sample size for Paper 3 (Chapter 6) was therefore 17.

3.3.2 Inclusion criteria and rationale

The inclusion and exclusion criteria are shown in Table 3-1 and Table 3-2 respectively.

Table 3-1: Inclusion criteria and rational

Criteria	Rationale
Male	Cricket is a sport predominantly played by males and none of the nine high schools in Eastern Pretoria had female cricket teams.
Ages 13 to 19 years	This is the age range for adolescents that attend high school. According to the authors of the FMS, the screening can be applied to athletes of any fitness level and age and would reveal information about those athletes who will experience setbacks and injuries with increased activity. The bowlers of various ages within the above mentioned range were therefore tested as one group.[19]

On the active roster at the start of the competitive cricket season.	As the players are monitored throughout the season they should be included in the active roster and available for selection for any of the school teams at the start of the season.

Table 3-2: Exclusion criteria and rationale

Criteria	**Rationale**
Injured pace bowlers at the start of the season	The FMS is designed for individuals who do not have a known musculoskeletal injury or current pain complaint.[19]

3.4 Setting

The rugby clubhouse of Hoërskool Menlopark, Pretoria, South Africa served as the on-site laboratory for the purposes of this study.

Three sections were set up: Section 1 was used for the completion of the pre-season questionnaires and signing of informed consent. Section 2 was used for USI and was equipped with a plinth, pillow, ultrasound gel and the ultrasound unit. Section 3 was used for the performance of the FMS and was equipped with the standard FMS equipment (a 1.2 m dowel, hurdle step, 2”X6” board and tape measure (Figure 3-1), ten OptiTrack® camera's, ground plate and laptop for recording of the FMS movements.



Figure 3-1: FMS equipment (http://oasis-fitness.com/shop/fms-functional-movement-testing-kit/)

3.5 Instrumentation and data collection

3.5.1 Standard FMS score sheets

The FMS score sheet was used to record test scores (Appendix B).

3.5.2 DP-6600 Digital ultrasonic imaging system®

A detailed description of the DP-6600 Digital ultrasonic imaging system®, used for the measurement of the abdominal wall muscles as well as literature related to the reliability and validity of the method is described in Paper 1 (Chapter 4). Image numbers and corresponding muscle thickness measurements for each participant were recorded on the specifically designed sheet (Appendix C).

3.5.3 OptiTrack® optical motion capture system

A detailed description of the OptiTrack® optical motion capture system used for the capture and analysis of the DS movement as well as literature related to the reliability and validity thereof is described in Paper 3 (Chapter 6)

3.5.4 Self-administered questionnaires

The same standard self-administered pre-season (Appendix D), in-season (Appendix E) and post-season (Appendix F) questionnaires were used for the purposes of Paper 1 and 2. These questionnaires were used to collect information related to the nature, extent and treatment of injuries that occurred in the past, during the season and unresolved injuries at the end of the season respectively. A detailed description of the pre-season and in-season questionnaires used to collect data as well as the validity thereof is described in Paper 1 and Paper 2.

3.6 Data collection procedures

3.6.1 Ethical clearance

Ethical clearance was granted by the Human Research Ethics Committee of the University of the Witwatersrand (Medical) (M130657) (Appendix G). Permission to conduct the study was also obtained from the Gauteng Department of Education (GDE) (Appendix H). The principals of the selected schools received an information leaflet (Appendix I) relating to the purpose and methodology of the study. Principals were requested to provide written informed consent to participate in the study (Appendix J).

Information leaflets were distributed to each bowler (Appendix K) and to the parents of the bowlers younger than 18 (Appendix L). The protocol was verbally explained and questions answered. All participants were informed that their participation were voluntary even if their parents agreed to it. Each of the participants were informed of their right to withdraw from the study at any time without suffering any consequences.

Consent to participate in the study as well consent for video capturing FMS movements, was sought from parents of the participants younger than 18 (Appendix M and O) or from the bowlers themselves if 18 years old or older (Appendix N and P).

There were no specific ethical considerations with regard to the interventions. USI does not cause any discomfort and the FMS guidelines state that should a participant experience any pain during any of the movements the screening should be ceased and the specific painful area assessed with the selective functional movement assessment (SFMA) that did not fall within the score of the study. Participation in the study did not disrupt regular schooling or training sessions.

Results of the study participants' biomechanical FMS assessment and USI were made available to the individuals and, if the participant signed a release of medical information form, also to their coaches. The researcher provided education on how to improve the identified asymmetries, weaknesses and limitations and the risk of injury.

To maintain confidentiality and anonymity, all participants were assigned a study number for identification. Checklists were kept in the researcher's office, locked in a cabinet and only the researcher and research assistant had access to the data files.

3.6.2 Pilot study

A pilot study was performed to test and trouble-shoot the research methodology and make the necessary adjustments.

3.6.2.1 Objectives of the pilot study

The objectives of the pilot study were to:

- Test the intra-rater reliability of the USI measurements and FMS scoring.
- Familiarise the research assistant with the research methodology and her role.
- Establish the time it takes to complete the testing procedure on a participant.

3.6.2.2 Methods of the pilot study

Pilot study sample selection

The kinematic system set-up, marker placements, performance and scoring of the FMS movements and the subsequent adjustments to optimise the on-site laboratory is a timely process. For this reason, only two participants were included in the testing of the intra-rater reliability of the FMS as well as the testing of the workings (i.e. that all markers were visible and could be tracked when the DS was performed) of the kinematic system. The FMS scores and kinematic data collected during the pilot study, however, were not included in the main study due to minor adjustments of the camera set-up after the results of the pilot study but the data related to intra-rater reliability of the FMS were analysed.

Ten participants, other than those included in the main study, were included in the pilot study to test the USI methods and the user friendliness of the self-administered questionnaires. The pilot study sample was randomly selected from another school that was not considered for the main study. The inclusion and exclusion criteria was the same as the main study (See Chapter 3, section 3.2.3 and 3.2.4).

Pilot study procedure

The pilot study data collection procedure was exactly the same as the procedure for the main study (See Chapter 3, section 3.4.3).

The intra-rater reliability of the FMS and the testing of the kinematic system was done simultaneously. To test the intra-rater reliability of the FMS, the researcher scored and recorded the two selected pilot study participants' FMS performances. These pilot study scores were later compared to the scores these two participants achieved during the main study which was four days later.

To test the intra-rater reliability of the USI measurements the test-retest method was used. The first muscle thickness measurements were done and recorded.

Two days after the first measurements were taken another measurement of the muscles using the same ten participants was done and recorded. To determine the correlation between the two ultrasound measurements the intra-class coefficient (ICC) was calculated at a 95% confidence interval. Considering the sample size, the results were interpreted according to guidelines as set out by Cicchetti.[94]

Score	Interpretation
0-0.40	Poor
0.41-0.59	Fair
0.60-0.74	Good
0.75-1.00	Excellent

3.6.2.3 Results from the pilot study

Only a few concerns regarding the methodology were noted.

Kinematic movement analyses

Some of the light reflective markers fell off when some of the FMS movements were performed. Another brand of double sided tape was used to improve the adhesiveness of the markers during the main study. During the performance of some of the movements an insufficient number of markers were visible on screen. The arrangement and angles of some of the cameras were adjusted until a sufficient number of markers were visible on screen for each of the movements.

FMS scoring and recording

The FMS score sheet was found to be user-friendly and scores were easily recorded. There were no differences between the first and second scores for any of the FMS movements for either of the participants.

It was therefore concluded that the intra-rater reliability of the FMS was sufficient.

Rehabilitative ultrasound imaging

There were no specific challenges with the execution of the USI or the recording of the measurements. The ICC (3,1) for determining between-day intra-rater reliability for the resting measurements for the IO, EO and TA muscles ranged from 0.94-0.99. During the performance of ADIM the ICC result of measurements were between 0.81-0.99. In terms of activated percentage change of muscle thickness the highest ICC result was obtained from the dominant IO (0.92) with 95% confidence interval from 0.71 to 0.98. The ICC and CI at 95% confidence level for each muscle, rested and activated as well as activated % change, during ADIM are summarised in Table 3-3.

Table 3-3:Interclass correlation coefficient (ICC) and 95% confidence interval (CI) for resting, activated and activated % change for the USI measured muscle thickness of TA, EO and IO muscles during ADIM.

	Rested ICC (CI)	ADIM ICC (CI)	ADIM % change (CI)
ND TA	0.94 (0.78-0.98)	0.81 (0.41-0.95)	0.73 (0.23-0.93)
DOM TA	0.96(0.85-0.99)	0.99 (0.96-1.00)	0.89 (0.62-0.97)
ND IO	0.99 (0.96-1.00)	0.93 (0.75-0.98)	0.85 (0.51-0.96)
DOM IO	0.97(0.88-0.99)	0.98 (0.67 -0.99)	0.92 (0.71-0.98)
ND EO	0.99(0.96-1.00)	0.95 (0.76-0.99)	
DOM EO	0.99(0.96-1.00)	0.92 (0.64-0.98)	

ND=Non dominant; DOM=Dominant; ADIM=abdominal drawing-in manoeuvre; TA=Transverses Abdominis muscle; IO=Internal Oblique muscle; EO=External Oblique muscle

In this study, the between day intra-rater reliability of rested TA thickness was slightly higher, while that of TA ADIM% change was similar to Koppenhaver et al. (2009) [18] who reported ICC3,2 values of 0.93 (0.85-0.97) and 0.73 (0.43-0.87) respectively. The intra-rater reliability of rested and activated IO as well as rested EO was higher compared to ICC3,1 values of 0.92 (0.82-0.97), 0.94(0.86-0.97) and 0.97 (0.93-0.98) reported by Park (2013).[95] Koppenhaver et al. (2009) [18] and Park (2013)[95] concluded that, based on these values, USI measurements by a single examiner was highly reliable. Therefore, considering that the design and findings for this current study was comparable to the last mentioned studies, the researchers considered the intra-rater reliability of the measurements to be high.

Injury monitoring questionnaires

No ambiguities or other difficulties with the standard questionnaire were reported and the questionnaire remained unchanged.

3.6.3 Main study

The main study consisted of two parts:
Part A: To determine the association between pre-season FMS scores and USI measurements in the prediction of injuries among pace bowlers.
Part B: To determine the concurrent validity of the FMS DS.

The data for both parts of the study were collected simultaneously as set out in Figure 3-3. The main study lasted for a total of three months and two weeks (Sep-mid Dec 2014). During the first week participant FMS performances were scored, kinematic data collected and abdominal muscle thicknesses captured. During the next three months that followed, injury monitoring took place monthly.

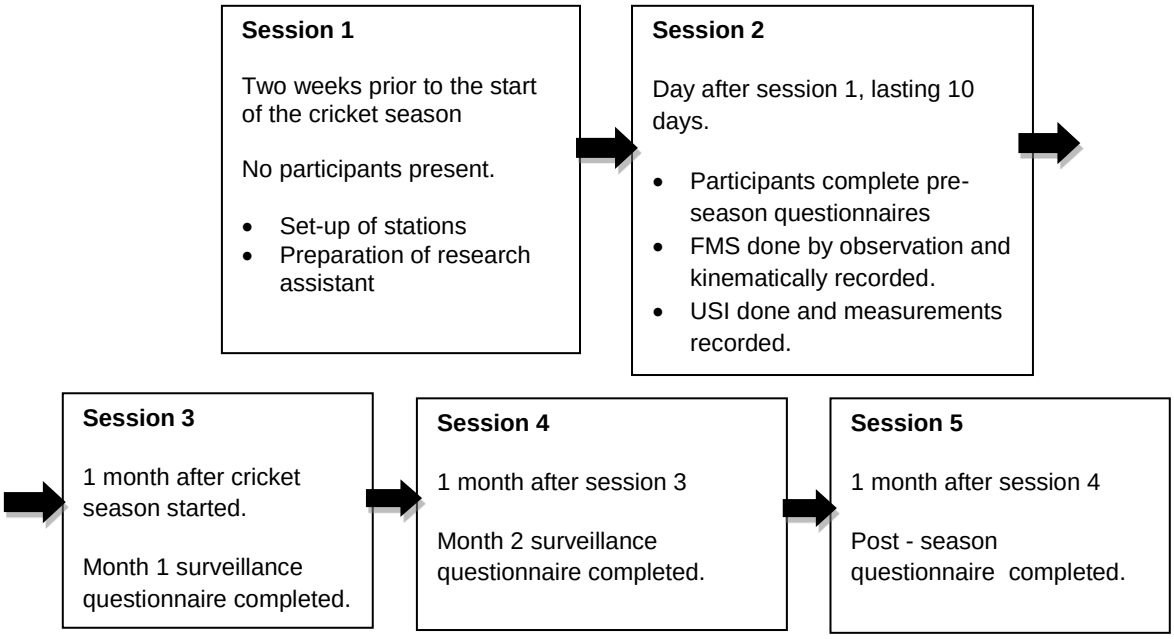


Figure 3-2: Main study procedure

3.6.3.1 Session 1: Two weeks prior to the start of the cricket season

Preparation of the research assistant

The research assistant was trained in:

a. Positioning of the light reflective markers on the predetermined anatomical land marks.

b. Operation of computer software for kinematic recording of the FMS movements.
c. Capturing the USI image of the muscles that were measured.

3.6.3.2 Session 2: Completion of pre-season standard questionnaire, USI measurements and FMS evaluations

Participants were asked to complete the standardised pre-season questionnaire (Appendix D).

Rehabilitative ultra-sound imaging

Participants were asked to position themselves in a supine hook position on a plinth. Resting and activated (ADIM) images of the TA, IO and EO muscles were captured using the DP-6600 Digital ultrasonic imaging system®. The researcher is a qualified physiotherapist and trained in the use of USI for measurement of lateral abdominal muscle thickness and captured all images. After images were captured, muscle thicknesses were measured, using in-screen callipers, and recorded by the researcher and research assistant. A detailed description of the procedures related to the USI of the lateral abdominal wall musculature is described in Paper 1 (Chapter 4).

Functional Movement Screening and Kinematic measurement/recording

FMS performance rating and collection of kinematic data from participants occurred simultaneously. The Optitrack® system requires the participants to wear reflective markers to track movements by a group of cameras. The markers were placed on predetermined anatomical landmarks (See Figure 6-1). The participants were asked to perform the seven FMS movements, as described in Appendix A.[72] FMS testing was conducted by a physiotherapist, who is experienced in using the FMS in daily practice and scores were recorded on the FMS score sheet (Appendix B). A detailed description of the data collection procedures related to the FMS testing procedure is described in Paper 2 (Chapter 5). Simultaneously, the researcher and research assistant monitored tracking of

the markers during the performance of the DS. After data related to marker tracking was collected data was analysed using Matlab (Version 7.2, The Matworks, Inc., Natick USA). A detailed description of the procedure related to the kinematic analyses of the FMS DS is described in Paper 3 (Chapter 7).

3.6.3.3 Session 3 and 4: Completion of monthly surveillance questionnaires

Session three was scheduled one month after the cricket season started and session four followed one month thereafter. During these sessions the participants were asked to complete the monthly surveillance questionnaires (Appendix E). Questionnaires were electronically mailed to participants of schools other than Hoërskool Menlopark to be completed. Hard copies were then collected from the schools. Participants from Hoërskool Menlopark completed the questionnaires at the laboratory.

3.6.3.4 Session 5: Completion of the post-season questionnaires

Session 5 was scheduled at the end of the year, after all matches for the year were played. This was approximately 4 months after the initial pre-season questionnaires were completed. During these sessions the participants were asked to complete the post-season surveillance questionnaire (Appendix F).

3.7 Statistical analyses

All data was captured in an Excel spreadsheet and all statistical procedures were performed on SAS Release 9.2 (SAS Institute for advanced analytics, NC, USA).

All continuous variables were summarised by mean, standard deviation, median, minimum and maximum values. Categorical variables were summarised by frequency counts and percentage calculations. The Shapiro-Wilk test was used to determine the normality of distribution of the data.

The statistical methods used for analyses of demographic data as well as data related to the studies specifically, is described separately in the individual papers.

CHAPTER 4

4 PAPER 1: ASYMMETRICAL ABDOMINAL MUSCLE MORPHOMETRY IS PRESENT IN INJURY-FREE ADOLESCENT CRICKET PACE BOWLERS: A PROSPECTIVE OBSERVATIONAL STUDY

Martin C, Olivier B, Benjamin N. (2016) Asymmetrical Abdominal Muscle Morphometry is Present in Injury-Free Adolescent Cricket Pace Bowlers: A Prospective Observational Study *Physical Therapy in Sport (conditionally accepted)*

At the time of this dissertation submission, Paper 1 was conditionally accepted at *Physical Therapy in Sport,* as an original article. For the purposes of this dissertation 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, although the reference style was kept similar to that of the rest of the document.

4.1 Original article

Title: Asymmetrical Abdominal Muscle Morphometry is Present in Injury-Free Adolescent Cricket Pace Bowlers: A Prospective Observational Study

Abstract

Objectives: This study aimed to determine if abdominal muscle thickness, activation and symmetry is associated with prospective in-season injury among adolescent cricket pace bowlers.

Design: A quantitative, prospective, observational study design was used.

Setting: Data was collected at an indoor venue at a secondary school.

Participants: 28 injury-free, male, adolescent pace bowlers between the ages of 13 and 18 years participated.

Main outcome measures: Muscle thickness of the transversus abdominis (TA), internal oblique (IO) and external oblique (EO) muscles were measured at rest and during an abdominal drawing-in maneuver (ADIM) i.e. activation, using ultrasound imaging. Incidence of injury was monitored monthly during the cricket season.

Results: Thickness of the non-dominant IO at rest was greater than the dominant side for pace bowlers who remained injury free during the cricket season ($p=0.01$, effect size (ES)=0.65). This was however not the case for bowlers who sustained injuries ($p=0.47$; ES=0.24). The TA percentage change during ADIM (activation) on the dominant side was less in bowlers who sustained non-contact injuries (to various body regions) compared to those who remained injury free ($p=0.03$; ES=1.17).

Conclusions: Asymmetry in IO thickness may play a protective role against injury, whilst poor TA activation on the dominant side may pose a risk to injury.

Key words: cricket; bowler; injury; ultrasound imaging

INTRODUCTION

Retrospective studies done by Milson, Barnard and Stretch (2007)[24] and Stretch and Trella (2012) [22], established that the majority of injuries sustained by school boy cricketers were during pace bowling. A combination of risk factors related to the adolescent growth spurt[96] and those specifically related to pace bowling could explain the above finding. Risk factors predisposing pace bowlers to injuries include previous injury, shoulder internal rotation strength deficit, compromised lumbar proprioception and disc pathology, faulty biomechanics and high bowling workload.[46] Core muscle stability is also important in the prevention of lower extremity injury among athletes.[97] Risk factors for injury specifically related to adolescents include the presence of growth cartilage, existence of muscle imbalance and pressure to compete despite pain and fatigue.[96]

A stable core allows an athlete to control the position and motion of the trunk over the pelvis thereby allowing production, transfer and control of force and motion to distal segments when complex, integrated athletic activities are performed.[5] Simply put, proximal core stability allows more efficient distal mobility. Performance of the abdominal drawing-in maneuver (ADIM) activates the deep stabilising muscles, which includes the Transverse abdominis (TA) and Internal oblique (IO), and is one of the components associated with good core stability.[6]

Ultrasound imaging (USI) is a safe, non-invasive technique used in various studies to evaluate the resting and activated thickness of the TA, IO and EO muscles.[14] This technique has been used to measure abdominal muscle activation and quantify muscle morphology and behaviour.[18] USI has been validated as a means of measuring the size and symmetry of various muscles when compared to magnetic resonance imaging (MRI) and as an indicator of muscle activation with indwelling electromyography (EMG).[98] USI is best performed by a trained practitioner to evaluate muscle structure and patterns of activation.[14] ADIM preferentially activates the TA and increased thickness of this muscle has been observed and measured with real time USI during the performance of this maneuver.[99] This exercise is not only often prescribed to

improve lumbar spine stability[14] but also used as a performance test to assess change in TA, OI and EO thickness.[1] USI is considered valid for assessing sub-maximal contractions of the abdominal wall in various populations, and the use thereof during the ADIM is an appropriate method for evaluating the structure and function of the lateral abdominal muscles in pace bowlers.[13]

The association between abdominal muscle thickness as well as altered recruitment patterns of these muscles and existing pain has been well documented. Teyhen et al. (2009) [100] investigated recruitment patterns of TA, IO and EO in individuals with unilateral lower back pain and found decreased TA activation during the performance of ADIM when compared to healthy individuals. Similarly, Hides, et al. (2010)[70] found that elite cricketers with lower back pain have excessive voluntary contraction of TA and IO during ADIM compared to asymptomatic cricketers.

Studies conducted by Olivier et al. (2013)[43] and Hides et al. (2006)[6] highlighted muscle adaptations in thickness and activity as a result of the asymmetrical nature of the bowling action. Both studies found that resting IO on the non-dominant side of these cricketers was thicker than on the dominant side. Asymmetry of both resting and activated trunk muscle thickness, might imply an abnormal load on the spine and has been associated with lower back pain in the general population.[63] However, some research suggest that these asymmetrical adaptations develop to accommodate the demands of sport-specific skills and therefore may play a protective role as opposed to being a predisposing factor to injury.[101,102]

Injury during adolescence can cause long term disability for the athlete.[103] Therefore, identifying and addressing any risk factors early on can have a significant impact on the athlete's career as well as health care costs. If the association between USI measured abdominal muscle thickness and injury is high, health and conditioning professionals should consider implementing this screening procedure, which is both user-friendly and efficient, in a clinical setting. This may enable them to identify those individuals at risk of sustaining an injury. Future research could then focus on the effectiveness of injury prevention

programs, aimed at training and rehabilitation of the lateral abdominal muscles, in the prevention of injury. These programs could be implemented in an attempt to decrease risk of injury among pace bowlers.

Therefore, the aim of this study was to investigate the association of the lateral abdominal muscle morphometry, in terms of rested and activated thickness as well as side-to-side symmetry, and prospective injury in a group of adolescent cricket pace bowlers.

METHODOLOGY

Study design

This was a quantitative, prospective, observational study.

Study setting and participants

Twenty-eight participants, from nine cricket playing high schools, in Pretoria South Africa, who met the inclusion criteria (male, aged 13-18, injury free, pace bowlers) were randomly selected using computer generated numbers. Data collection took place in 2014, at one of the nine cricket playing secondary schools. All participants and their guardians provided written informed consent and had the right to withdraw from the study without suffering any repercussions. The human research committee of the associated tertiary institution provided ethical approval.

Outcome variables

Standard self-reporting questionnaires

General information regarding the bowler (type of bowler, self-reported bowling speed, and hand dominance) as well as information regarding the status, nature and prevalence of any injury sustained in the past was included in the pre-season questionnaire. Information regarding the nature of injuries sustained and treatment received was included in the pre-, in-, and post- season questionnaires.

This established questionnaire has previously been used and deemed valid in the study conducted by Olivier et al. (2015)[104],[105] for collecting the same information among club-level pace bowlers.

For the purposes of this study an injury was defined as: damage or harm of any body region, whilst participating in a sporting activity that resulted in loss of at least one day of training or play, or that occurred during a sporting activity that required medical attention (emergency room, physiotherapy, etc.). Contact injuries were defined as any injury sustained due to collision with another player or object (e.g. ball, bat, ground), while non-contact injuries were all injuries sustained in a manner not involving contact (e.g. overuse injuries).

Muscle thickness measurements

Muscle thickness of the transversus abdominis (TA), internal oblique (IO) and external oblique (EO) muscles were measured at rest and during ADIM i.e. activation, using ultrasound imaging.

Procedures

A pilot study was conducted to test the between-day intra-rater reliability of the ultrasound measurements using the test–retest method. Ten participants, other than those included in the main study, who met the same inclusion criteria, were included in the pilot study. Muscle thickness measurements were done and recorded. Two days later the procedure was repeated on the same ten participants and results recorded. To determine the correlation between the two ultrasound measurements the intra-class coefficient (ICC) was calculated at a 95% confidence interval.

Data was collected in three stages. During the first stage, two weeks prior to the start of the season, participants completed the pre-season questionnaire. Resting and activated thickness of the TA, IO, EO muscles were also measured and

recorded at this time. Participants were then asked to complete monthly injury monitoring questionnaires for the next three months and post-season questionnaires were administered at the end of the season. A three-month evaluation period was selected as players in a school setting change from one age group to another.

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) was used to measure size and symmetry of the lateral abdominal stabilisers. The researcher underwent training in the use of the equipment which included handling and placement of the transducer on the correct anatomical landmarks, identifying the EO, IO and TA muscles on screen, capture and labeling of images, once identified on screen, and measurement of muscle thickness using on-screen calipers. The ultrasound measurements were done in brightness (B) mode. The ultrasound echo was recorded as a cross-sectional gray-scale image.[106,43]

The participant was positioned on a plinth in supine hook-lying with the head in mid-line, arms across the chest.[14] The transducer head was placed 2.5 cm anterior to the mid-axillary line in the region between the iliac crest and the anterior superior iliac spine (ASIS) in the transverse plane.[107] The medial edge of the TA was positioned as the medial edge of the ultrasound image.[43,106] Finally, placement was adjusted to ensure that, at rest, the facial borders of the three muscles were parallel on the screen. This position was chosen as all three muscles are well represented and easy to measure on the image.

To perform ADIM participants were taught, with a standard set of instructions, to gently pull the lower abdomen up and in towards the spine at the end of expiration and hold for ten seconds.[1] Participants had the opportunity to practice the ADIM, while looking at the ultrasound monitor for visual feedback, six times (three visual feedbacks per side) before images that would be used in the main study were captured. The images were taken at the end of expiration with the glottis open to avoid bracing and control the influence of respiratory cycle on thickness.[43,108]

Three sets of images of the left and right IO, EO and TA were taken during rest and whilst performing the ADIM. The transducer position was kept constant for the measurement of one set (i.e. one rested and activated image on one side) of images[100], but removed from the skin and reapplied to the same anatomical landmarks between each set. The research assistant recorded the frame number of each image. Of the three sets of images, the set with the best quality was selected for analyses.

The researcher, who was blinded to the participant's identity and injury history, measured the rested and activated thickness of TA, IO and EO muscles using on-screen calipers. To minimise the memory effect of repetitive measurements, the images of all participants from the first testing session were analysed before images from the second testing session, with a two day interval between analyses.[108] Measurements were taken from the inside border of the hyperechoic region to the next, in the center of the muscle belly (i.e. at maximal muscle width) by using a vertical straight line through the middle of the image.[43] Measurements were conducted perpendicular to the muscle fascia. Figure 4-1 demonstrates the ultrasound images of measured resting and activated muscle thickness respectively. At the time of measurement, the images had not yet been labelled according to participant number, side and contractile state (rested or activated). Only after measurements were taken, were images labelled by the research assistant and data was captured in an Excel spread sheet. The difference between resting and activated thickness was calculated and expressed as a percentage of resting thickness i.e. activated percentage change.

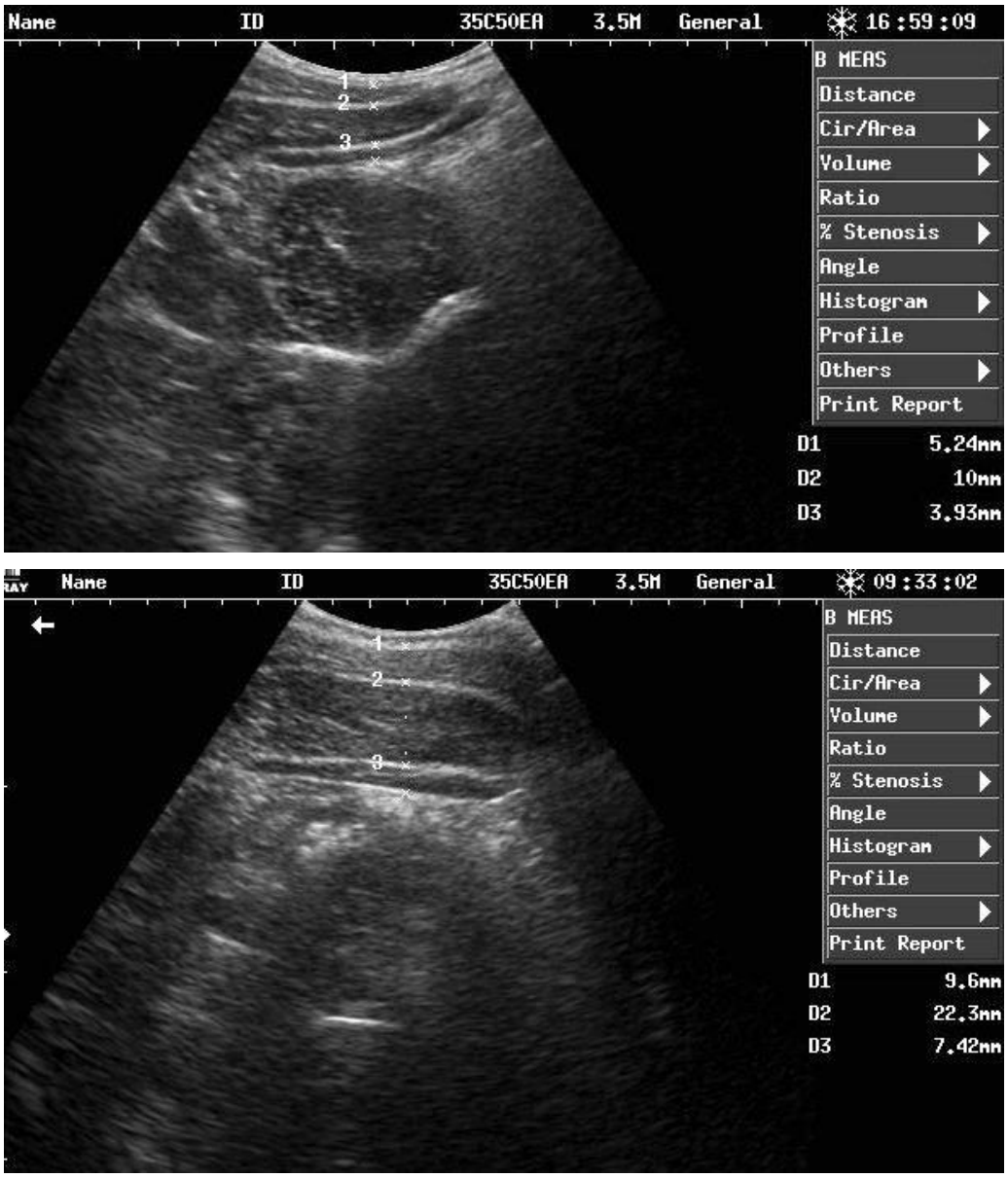


Figure 4-1 Ultrasound images of lateral abdominal muscles (a) measured thickness at rest and (b) measured thickness in ADIM
*D1=External Oblique D2=Internal Oblique D3=Transversus Abdominis

Statistical analysis

Statistical analysis was accomplished using SAS Release 9.2 (SAS Institute Inc, Cary, NC, USA). Test-retest reliability was established by calculating ICC values at 95% level of confidence. Considering the sample size, the results were interpreted as follow: 0-0.40=Poor, 0.41-0.59=Fair, 0.60-0.74=Good, 0.75-1.00=Excellent.[94] Muscle thickness at rest was reported for TA, OI and OE while thickness % change during ADIM was reported for TA and OI. Thickness

percentage change was calculated as follows: muscle thickness in contracted state minus muscle thickness at rest, divided by muscle thickness at rest multiplied by 100.[43]

The Shapiro-Wilk test was used to determine the normality of data of all respective groups and variables and subsequently all data, for the group and subgroups, was treated as parametric. The assumption of homogeneity of variance for the group, subgroups and respective variables was confirmed using Levene's test. The differences in muscle morphometry between the injured (as a group as well as contact and non-contact injuries respectively) and non-injured bowlers were compared using the two-tailed, independent t-test. The differences in muscle morphometry between dominant and non-dominant sides were compared using the two-tailed paired student's t-test. Statistical significance was set at $p \leq 0.05$. The effect sizes of the differences in muscle thickness and activity were calculated using Cohen's d. Qualitative interpretation of Cohen's d were as follow: small effect >0.15 and <0.40; medium effect ≥0.40 and <0.75; large effect ≥0.75 and <1.10; very large effect ≥1.10 and <1.45; huge effect ≥1.45.

RESULTS

Test-retest reliability

The ICC (3,1) for determining between-day intra-rater reliability for the resting measurements for the IO, EO and TA muscles ranged from 0.94-0.99. During the performance of ADIM the ICC result of measurements of all muscles was above 0.9. In terms of activated % change of muscle thickness the highest ICC result was obtained from dominant IO (0.92) with 95% confidence interval from 0.71 to 0.98.

Demographic and anthropometric information

Twenty-eight pace bowlers participated in this study. There were no statistically significant differences in any of the demographic variables (age) or anthropometric variables (height, weight and body mass index (BMI)) between the non-injured and injured bowlers (Table 4-1). As body composition variants were similar, comparisons between the non-injured vs injured bowlers, non-

injured vs contact injury group and non-injured vs non-contact injury group could be made. Only two of the bowlers evaluated were left handed.

Table 4-1:Demographic information: Injured vs non-injured groups and contact vs non-contact injuries (n=28).

	Injured (n=11) m (SD)	**Non-injured (n=17) m (SD)**	**t-test[a] (p-value)**	**Contact Injuries (n=5) m (SD)**	**t-test[b] (p-value)**	**Non-contact Injuries (n=6) m (SD)**	**t-test[c] (p-value)**
Age (years)	16.82 (1.70)	16.44 (0.78)	0.36	17 (1.41)	0.29	16.67 (0.94)	0.64
Height (m)	1.84 (0.04)	1.83 (0.69)	0.83	1.83 (4.09)	0.89	1.85 (2.99)	0.67
Weight (kg)	80.09 (9.02)	77.00 (7.48)	0.33	81.2 (10.52)	0.83	79.12 (7.73)	0.56
BMI (kg/m^2)	23.76 (2.96)	22.96 (2.37)	0.43	24.31 (3.15)	0.31	23.31 (3.01)	0.78

a-difference between injured and non-injured bowlers; b-difference between bowlers who had contact injuries and non-injured bowlers; c-difference between bowlers who had non-contact injuries and non-injured bowlers
BMI=body mass index;

Injury Incidence

A total of 14 injuries were reported by 39.3% (n=11) bowlers during the season. Five bowlers sustained contact injuries while six sustained non-contact injuries. Three of the bowlers sustained two injuries. The body regions where injury occurred are summarised in Table 4-2. Most injuries occurred during fielding (38.5 %) then bowling (30.8%) and batting (8%). The remaining 22.7% of the injuries occurred during warm-up or an incident during training or a match which the bowler could not specifically identify or was of gradual onset that the bowler could not attribute to one of the specific cricketing disciplines.

Table 4-2: Body regions where injury occurred

Body region	Contact	Non-contact	Number of injuries
Upper limb	3	0	3 (21.43%)
Lower limb	1	2	3 (21.43%)
Lower back	2	4	6 (42.86%)
Other	0	2	2 (14.29%)
Total	6	8	14

Abdominal muscle thickness and activation asymmetry between dominant and non-dominant sides

The IO muscle thickness at rest was greater on the non-dominant side than on the dominant side for the entire group of injury free bowlers as tested at the start of the season (p=0.02; ES=0.49) and especially for the sub-group of bowlers who did not sustain injuries during the course of the season (p=0.01; ES=0.65) (Table 4-3). A statistically significant difference (p=0.04) in the ADIM percentage change between the dominant and non-dominant IO muscle of the group the non-contact injury group (n=6) was found although the ES was very small (ES=0.08) (Table 4-4).

Table 4-3:Non-dominant vs dominant thickness at rest and ADIM percentage change for the whole group and for the bowlers who did not sustain an injury during the season (non-injured bowlers).

		GROUP (n=28)[a]				NON-INJURED (n=17)[b]			
		ND m (SD)	D m (SD)	p-value	ES Cohen's *d*	ND m (SD)	D m (SD)	p-value	ES Cohen's *d*
REST (mm)	TA	4.88 (1.21)	4.65 (1.02)	0.32	0.21	4.88 (1.05)	4.47 (0.70)	0.15	0.47
	IO	11.65 (2.96)	10.28 (2.68)	0.02*	0.49	11.38 (3.02)	9.56 (2.57)	0.01*	0.65
	EO	7.02 (1.72)	6.80 (2.09)	0.12	0.11	6.88 (1.75)	6.32 (1.60)	0.57	0.34
ADIM % CHANGE	TA	63.94 (50.11)	71.86 (42.95)	0.51	0.17	62.83 (57.37)	83.45 (44.90)	0.23	0.40
	IO	37.63 (31.19)	46.04 (44.78)	0.25	0.22	32.89 (30.35)	48.53 (50.47)	0.11	0.39

a-the entire group of injury free bowlers as measured at the start of the season; b-the group of bowlers who did not sustain an injury during the season; *statistically significant
ES=effect size; ND=Non dominant; D=Dominant; ADIM=abdominal drawing-in manoeuvre; TA=Transverses Abdominis muscle; IO=Internal Oblique muscle; EO=External Oblique muscle

Abdominal muscle thickness and activation difference between the injured and non-injured bowlers

No statistically significant differences in terms of abdominal muscle thickness or activation were found between the non-injured and injured group (comprising of contact and non-contact injuries) (Table 4-4). When the injured group was divided into sub-groups, dominant IO (p=0.02; ES=1.35) and OE (p=0.03; ES=1.00) at rest were thicker in those who sustained contact injuries than those who were not injured. ADIM percentage change on the dominant side for TA was less for those who sustained non-contact injuries than those who remained injury free (p=0.03; ES=1.17) (Table 4-5).

Table 4-4:Non-dominant vs dominant thickness at rest and ADIM percentage change for injured and non-injured bowlers.

		INJURED (n=11)[a]				CONTACT INJURIES (n=5)[b]				NON-CONTACT INJURIES (n=6)[b]			
		ND m (SD)	**D m (SD)**	**p-value**	**ES Cohen's *d***	**ND m (SD)**	**D m (SD)**	**p-value**	**ES Cohen's *d***	**ND m (SD)**	**D m (SD)**	**p-value**	**ES Cohen's *d***
REST (mm)	**TA**	4.88 (1.49)	4.92 (1.37)	0.93	0.03	5.06 (2.06)	4.98 (2.11)	0.93	0.04	4.73 (0.97	4.88 (0.44)	0.58	0.2
	IO	12.06 (2.96)	11.39 (2.51)	0.47	0.24	13.77 (3.04)	12.66 (2.04)	0.46	0.2	11.13 (2.81)	10.33 (2.62)	0.64	0.29
	EO	7.22 (1.23)	7.55 (2.59)	0.69	0.15	8.29 (1.95)	8.74 (3.24)	0.80	0.18	6.33 (0.91)	6.55 (1.56)	0.76	0.18
ADIM % CHANGE	**TA**	65.66 (38.83)	53.95 (34.25)	0.43	0.32	79.19 (34.70)	73.41 (34.71)	0.84	0.17	54.38 (41.43)	37.73 (26.23)	0.34	0.49
	IO	44.94 (32.48)	42.20 (36.23)	0.81	0.08	30.75 (19.05)	28.18 (37.61)	0.9	0.08	56.77 (38.08)	53.89 (33.67)	0.04*	0.08

a-the group of bowlers who sustained an injury during the season; b-the group of injured bowlers divided into contact injuries and non-contact injuries
ES=effect size; ND=Non dominant; D=Dominant; ADIM=abdominal drawing-in manoeuvre; TA=Transverses Abdominis muscle; IO=Internal Oblique muscle; EO=External Oblique muscle

Table 4-5:Thickness at rest and ADIM percentage change for injured vs non-injured group, bowlers who sustained contact injuries vs non-injured bowlers and bowlers who sustained non-contact injuries vs non-injured bowlers.

				INJURED VS NON-INJURED			NON-INJURED VS CONTACT			NON-INJURED VS NON-CONTACT	
VARIANT		**Injured (n=11)**	**Non-Injured (n=17)**	**T-test**	**Effect size**	**Contact (n=5)**	**T-test**	**Effect size**	**Non-contact (n=6)**	**T-test**	**Effect size**
		Mean (SD)	**Mean (SD)**	**(p-value)**	**(Cohen's *d*)**	**Mean (SD)**	**(p-value)**	**(Cohen's *d*)**	**Mean (SD)**	**(p-value)**	**(Cohen's *d*)**
ND REST (mm)	TA	4.88 (1.49)	4.88 (1.05)	1.00	0.00	5.06 (2.06)	0.79	0.12	4.73 (0.97)	0.77	0.15
	IO	12.06 (2.96)	11.38 (3.02)	0.56	0.23	13.17 (3.04)	0.26	0.59	11.13 (2.81)	0.86	0.09
	EO	7.22 (1.73)	6.88 (1.75)	0.62	0.20	8.29 (1.95)	0.14	0.42	6.33 (0.91)	0.76	0.91
D REST (mm)	TA	4.92 (1.37)	4.47 (0.70)	0.33	0.43	4.98 (2.11)	0.77	0.15	4.88 (0.44)	0.20	0.71
	IO	11.39 (2.57)	9.56 (2.57)	0.08	0.71	12.66 (2.04)	0.02*	1.35	10.33 (2.62)	0.53	0.90
	EO	7.55 (2.59)	6.32 (1.60)	0.18	0.58	8.74 (3.24)	0.03*	1.00	6.55 (1.56)	0.76	0.91
ND ADIM % CHANGE	TA	65.66 (38.83)	62.83 (57.37)	0.89	0.06	79.19 (34.70)	0.56	0.36	54.38 (41.43)	0.75	0.36
	IO	44.94 (32.48)	32.39 (30.35)	0.33	0.38	30.75 (19.05)	0.88	0.09	56.77 (38.08)	0.88	0.70
D ADIM% CHANGE	TA	53.95 (34.75)	83.45 (44.90)	0.06	0.75	72.41 (34.71)	0.75	0.36	37.73 (26.23)	0.03*	1.17
	IO	42.20 (36.23)	48.53 (50.57)	0.70	0.15	28.18 (37.61)	0.42	0.46	53.89 (33.67)	0.81	0.72

*statistically significant

ND=Non dominant; D=Dominant; ADIM=abdominal drawing-in manoeuvre; TA=Transverses Abdominis muscle; IO=Internal Oblique muscle; EO=External Oblique

DISCUSSION

In this study, the pre-season IO thickness at rest was higher on the non-dominant side compared to the dominant side for the whole group of bowlers that were all injury free at the start of the season. This same finding was evident in the sub-group of bowlers that remained injury free during the cricket season. As a group, the bowlers who sustained injuries during the season did not show any asymmetry which leads us to the assumption that the asymmetry in IO may protect the bowler against injury rather than predispose to injury. This is further endorsed by Gray et al. (2016)[101] who reported that the combined TA, IO and EO thickness was greater on the non-dominant side for adolescent, provincial bowlers without lower back pain. Another study reported that injury-free adult club level bowlers also had a thicker IO at rest on the non-dominant side.[43] However, a different finding was reported amongst elite cricketers where IO on the non-dominant side was thicker in those players with low back pain.[13] In the Hides, et al. (2007)[13] study, participants consisted of adult professional cricketers whereas this study as well as Gray, et al. (2016)[101] investigated adolescent bowlers. At professional level, bowlers' historical and current bowling load far exceeds that of bowlers at school boy level, which may have an effect on muscle development and subsequent difference in thickness measurements.

The asymmetry in the bowlers who remained injury free in this study contradicts the hypothesis that asymmetry of the core muscles predisposes an athlete to increased risk of injury as the generation and transfer of forces in the kinetic chain is altered.[40] Engstrom, et al. (2007)[40] found a strong association between quadratus lumborum (QL) asymmetry and the development of symptomatic pars interarticularis lesions in the lumbar spine of adolescent cricket fast bowlers. De Visser et al. (2007)[62] however found that when L3/L4 stress levels (i.e. mathematically calculated forces and moments) are highest during bowling, bowlers with asymmetrical QL thickness (where contralateral QL is thicker) have smaller stress changes compared to bowlers with symmetrical QL muscle thickness. They therefore concluded that asymmetry is not the cause of stress on the pars interarticularis and even suggest that asymmetry might help reduce stress.

The pace bowling action is an asymmetrical, dynamic, repetitive activity. Springer et al. (2006)[109] suggest that individuals who participate and practice unilateral rotational

sports are more likely to develop asymmetries. The asymmetries in injury free pace bowlers can therefore be explained by unilateral repetitive bowling action in which some muscles are preferentially activated and hypertrophied above others.[43,101]. Gray, et al. (2016)[101] and Olivier, et al. (2013)[43] acknowledge two reasons related to the biomechanics of bowling for IO asymmetry. Firstly, during the delivery stride the non-dominant IO contributes to forward rotation of the thorax and shoulders prior to and during ball delivery. Secondly, the same muscle contracts to assist in absorbing the high ground reaction forces generated with non-dominant front foot placement during the delivery stride. Repetitive exposure to this unilateral rotational action is likely to explain the observed IO asymmetry in the entire group of injury free pace bowlers at the start of the season.

While both this current study and that of Hides, et al. (2010)[70] highlight the association of TA activation and injury prediction, the level of activation (i.e. over- vs under activation) as risk factor is conflicting. In this current study, the dominant TA showed lower levels of activation in those who sustained non-contact injuries which was supported by a very large effect size. On the contrary Hides, et al. (2010)[70] found that cricketers with lower back pain have excessive contraction of the TA and IO compared to cricketers without lower back pain when performing ADIM. Also, participation in motor control training programs can normalise this excessive contraction.[71] The differences in results might be due to a number of differences between the participants and methods of the two studies. Firstly, the aforementioned authors investigated adult cricketers, as opposed to adolescent bowlers where muscle development has not yet matured. Training intensity of club and professional bowlers is much higher than those at school boy level and the aforementioned bowlers have more years of playing experience. Secondly, abdominal muscle contraction in both the last mentioned studies[70,71] was assessed during simulated weight-bearing conditions while there was no weight-bearing during muscle thickness measurement in our study. Furthermore, Hides, et al. (2010)[70] included all cricket players and not only bowlers as was the case in this current study.

A recent systematic review by Wong et al. (2013)[110] found that baseline dysfunction (i.e. decreased contraction thickness ratio) of TA could not predict clinical outcomes of low back pain (LBP). Similarly, another systematic review by the same authors,

found that changes in TA morphometry and activation after conservative management were unrelated to the improvement of pain intensity or LBP related disability.[111] Considering the findings of the above systematic reviews as well as conflicting findings between this current study and the Hides et al. (2010)[70] and Hides et al. (2016)[71] studies, the traditional emphasis placed on TA and its role in injury among the general and sporting population is challenged.

Rested, dominant IO and EO of the group that remained injury free, were thinner than those who sustained contact injuries (statistically significant with large to very large effect sizes) as well as those who sustained non-contact injuries (although not statistically significant, the effect sizes were large). The large effect sizes of insignificant differences of the above mentioned measurements may be explained by the small sample sizes of the contact injury (n=5) and non-contact injury (n=6) groups. Lakens (2013) [112] explains that Cohen's *d* can help explain confounding results in studies with small sample sizes where statistically significant differences are unlikely. The effect size indicates the size of the difference rather than confounding it to sample size.

The fact that the above findings were present in both those who sustained contact as well as those who sustained non-contact injuries, leads us to think that the abdominal muscle thickness plays a role not only in non-contact injury but perhaps also in the prevention of contact injury. When a pre-participation screening tool is developed it is of the utmost importance to consider all the sport-specific demands placed upon the athlete as well as any possible means of injury (contact or non-contact) to which the athlete could be exposed. It is assumed that contact injuries are less likely to be affected by muscle morphometry. For this reason, authors of other studies[101,13] who have investigated the relationship between muscle morphometry and injury, only included non-contact, overuse type injuries related to the bowling action. One must keep in mind that bowlers are also required to bat and field during training and games and are therefore also exposed to contact injuries by collision with the ball or ground with a body part when diving while fielding or batting.[24]

Measures to address contact injuries, such as those caused by collision with the ball, are primarily extrinsic forms of protection such as helmets and padding.[29] However, these are only worn by batsmen and fielders in certain positions (wicketkeeper and silly point). While bowling or fielding cricketers do not wear any protective gear and therefore have to rely on the appropriate structural integrity of the body, athletic ability (which includes speed, power, agility, reaction time and dynamic balance) and the correct technique in order to avoid or lessen impact caused by contact with the ball or ground.[29]

The abdominal wall musculature is a component of what is commonly referred to as "the core". The core controls both position and motion of distal body segments during integrated athletic activities[5] and improves performance and skill.[30] Improved athletic ability could manifest in greater acceleration of a batsman between wickets thereby eliminating the need to dive or lurch towards the crease to avoid a possible run-out scenario; or improved catching or fielding technique thereby preventing a collision between the ball and the body. It is because of the complex nature of cricket as a sport and the unequivocal role of the core in effective mobility of the limbs that this study includes upper limb, lower limb and back injuries in the definition of an injury.

In addition to enhanced athletic performance, a stronger core also allows for greater structural integrity of the body wall. Structural integrity is important in instances in which there may be a collision between two bodies: the body with the best structural integrity will endure the least amount of structural damage as the impact of the collision is better tolerated. Hence, structural damage is inversely related to structural integrity. Similarly, when the core is activated correctly it contributes to the structural integrity of the body[66] and can therefore, together with correct diving technique, affect the consequences of an impact with the ground when diving. Considering the contributions to both athletic ability as well as structural integrity, the researchers felt that abdominal muscle morphometry may also play a role in the prevention of contact injuries and have thus included both contact and non-contact injuries to any body region in this study.

Limitations

The results referring to the sub-analysis in which contact and non-contact injuries were compared should be interpreted with caution as a Type II error may have occurred and a significant effect could have been missed due to the low sample size. Future research should consider larger sample sizes which will allow for subgroup analysis. The effect of food consumption and prior history of lower back injury and the effects thereof on abdominal wall muscle thickness was not taken into account prior to the assessing the IO, EO and TA muscle thickness.

CONCLUSION

Abdominal muscle asymmetry, specifically a thicker IO on the non-dominant side, may play a protective role against injury in cricket pace bowlers. Future research should be conducted to investigate the possible protective role of asymmetrical abdominal musculature in athletes that participate in other unilateral, rotational sports. Poor TA activation on the dominant side may pose a risk to injury. Research should also consider the role of abdominal muscle thickness and ADIM percentage change in contact injuries in cricket players.

4.2 Linking notes for Chapters 1,2,4 and 5

This section contains information to clarify the link between Chapters 1 (Background), Chapter 2 Literature review), Chapter 4 (PAPER 1: ASYMMETRICAL ABDOMINAL MUSCLE MORPHOMETRY IS PRESENT IN INJURY-FREE ADOLESCENT CRICKET PACE BOWLERS: A PROSPECTIVE OBSERVATIONAL Study) and Chapter 5 (PAPER 2: THE FUNCTIONAL MOVEMENT SCREEN IN THE PREDICTION OF INJURY IN ADOLESCENT CRICKET PACE BOWLERS: AN OBSERVATIONAL STUDY). 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 first two objectives of this dissertation was to establish the association of two intrinsic risk factors, lateral abdominal muscle morphology and functional movement patterns, and in-season injury among adolescent cricket pace bowlers. Chapter 4 (Paper 1) addressed the first objective and reported an association between rested non-dominant IO thickness and under-activation of dominant TA and in-season injury among adolescent pace bowlers.

Paper 2 addressed the second objective and investigated the association between pre-season FMS score and in-season injury among adolescent pace bowlers. The findings have been documented in Chapter 5.

CHAPTER 5

5 PAPER 2: THE FUNCTIONAL MOVEMENT SCREEN IN THE PREDICTION OF INJURY IN ADOLESCENT CRICKET PACE BOWLERS: AN OBSERVATIONAL STUDY

Martin C, Olivier B, Benjamin N. (2016). The Functional Movement Screen in the prediction of injury in adolescent cricket pace bowlers: an observational study *Journal of Sport and Rehabilitation 24:1-30 (Published)*

At the time of this dissertation submission, Paper 2 was published at the *Journal of Sport and Rehabilitation,* 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, although the reference style was kept similar to that of the rest of the document.

5.1 Original paper

TITLE: The Functional Movement Screen in the prediction of injury in adolescent cricket pace bowlers: An observational study

ABSTRACT:

Context: The Functional Movement Screen (FMS) has been found to be a valid pre-participation screening tool in the prediction of injury among various athletes in different sports. The validity thereof in the prediction of injury among adolescent cricketers is yet to be established.

Objective: To determine if a pre-season FMS total score is a valid predictor of in-season injury among adolescent pace bowlers.

Design: Prospective observational quantitative study.

Setting: Bowlers performed the FMS before the start of the season. Injury incidence was monitored monthly throughout the season. The student t-test and Fisher's exact test were used to compare the FMS scores of the injured and non-injured bowlers as well as the injured and non-injured bowlers who scored ≤ 14.

Participants: 27 injury free, male adolescent pace bowlers.

Main Outcome Measures: The FMS (scoring criteria and score sheet) and standardised self-administered injury questionnaire.

Results: There was no difference between the non-injured group (16.55±2.57) and the injured (16.1±2.07) group in terms of FMS scores. There was no significant difference between injured and non-injured bowlers who scored ≤14. A total FMS score of 14 does not provide the sensitivity needed to assess injury risk among adolescent pace bowlers and no other accurate cut-off score could be calculated.

Conclusion: Pre-season observed total FMS score is a poor predictor of in-season injury among adolescent pace bowlers. Further research should be conducted to determine if a specific FMS test will be a more valid predictor of injury.

Key words: cricket; bowler; injury; Functional Movement Screen

Introduction

Cricket remains the most popular sport in Commonwealth and former Commonwealth countries in the world.[113] Internationally, all three formats of the game (test, fifty-over and twenty-over matches) are predominantly played by men but have become increasingly popular among women. At junior (under 19) level, national school boy teams also get the opportunity to play in various international matches including the under 19 World Cup that is held every four years. Although international, women's cricket competitions have been getting more exposure in recent years; it is not yet at the same level as the men's game. At school level popularity and participation in the game by girls has also not yet reached the same level as boys. These might be reasons why in majority of schools, especially those in Commonwealth countries, various male teams (grouped by age) but few, if any, female teams have been established.

Cricket requires three distinct disciplines, batting, bowling and fielding. Bowlers can be categorised as spin or pace bowlers. At professional level, pace bowlers aim to beat the batsman by deviations in speed (faster than 120km/hour) and direction of flight of delivery.[12] In contrast, spin bowlers add rotation to ball delivery, causing the ball to deviate from the original flight direction when it hits the ground.[35]

The pace bowling action requires a sequence of complex, high speed movements.[104] It consists of five phases namely run-up, pre-delivery stride, delivery stride, front- foot strike, ball release and follow through.[36] During the last phases the action requires a combination of lumbar spine extension, contra-lateral side flexion and ipsilateral rotation.[104] In addition, large ground reaction forces have to be counteracted during the front foot strike. Considering the above and the repetitive unilateral nature of bowling it is not surprising that young fast bowlers of all ages remain at greatest risk of sustaining injury.[7] Furthermore, this study also reported that bowling injuries mostly occur during run-up and delivery phases and that the body regions mostly affected were the lower limbs and back.

Although predominantly considered to be a non-contact sport, collision with the ball, another player, boundary rope, or ground predisposes cricketers to contact injuries.[24]

Stretch (2014)[7] found that young cricketers sustain proportionally less overuse injuries than elite players and were more susceptible to acute traumatic injuries. It should be kept in mind that bowlers are also required to bat and field during matches and training thus exposing them to contact injuries. Furthermore, no protective gear (e.g. helmets, padding), as is usually worn by batsman and wicketkeepers to lessen impact of collision, is worn when bowling or fielding. The player therefore has to rely on athletic ability and unrestricted movement patterns to execute correct fielding techniques (diving, running and catching) to either avoid or lessen impact of collision.

To ensure that young players remain injury free for as long as possible coaches, administrators and conditioning staff need to identify risk factors and develop preventative strategies.[77] A combination of extrinsic and intrinsic risk factors predisposes any athlete to injury. Intrinsic person-related risk factors include muscle asymmetry, core stability deficiencies and postural defects.[44] In addition, poor dynamic balance and asymmetrical strength and flexibility resulting in poor fundamental movement patterns, essential for complex athletic movements such as the bowling action, have also been associated with increased risk for injury among athletes in general.[8]

The Functional Movement Screen (FMS) has been developed as a comprehensive, pre-participation tool to screen the quality of any athlete's fundamental movement patterns, identify limitations and asymmetries and establish the athlete's risk for sustaining an injury.[8] To achieve a required task through normal movement, an integration of fundamental movement patterns with an appropriate mobility-stability balance is required.[19] However, in response to pain, weakness, tightness or structural abnormality, the human system adopts adaptive predictable protective movement patterns.[8] Eventually these adaptive movement patterns result in a decreased range of motion (ROM), muscle length changes and compromised strength. Therefore, an isolated screening, evaluation or treatment approach will not restore these movement impairments as a whole.

The FMS challenges these functional, fundamental movement patterns.[72] The seven fundamental movement patterns included in the FMS requires an interplay of strength, flexibility, ROM, coordination and balance[8] and forms the basis of more complex athletic movements. The seven FMS tests and movement aspects they challenge are

set out in Figure 5-1. The different movement patterns position the athlete in such a manner that deficits in the above mentioned fitness aspects are exposed. Additionally, clearing tests are done to clear the spine (with full spinal flexion and extension) and shoulder girdle (with internal rotation and flexion) of pain.

DEEP SQUAT (DS)  Bilateral, symmetrical and functional mobility of the hips, knees and ankles.	**ACTIVE STRAIGHT LEG RAISE (ASLR)**  Active hamstring and gastrocnemius flexibility while maintaining a stable pelvis
HURDLE STEP (HS)  Body stride mechanics during the asymmetrical pattern of the stepping motion.	**TRUNK STABILITY PUSH-UP (TSPU)**  Trunk stability while a symmetrical upper extremity motion is performed.
IN-LINE LUNGE (ILL)  Hip and trunk mobility and stability, quadriceps flexibility and ankle and knee stability.	**ROTARY STABILITY TEST (RS)**  Multi-plane trunk stability while upper and lower extremities are in combined motion.

SHOULDER MOBILITY (SM)	
 Bilateral shoulder R.O.M, scapular mobility and thoracic spine extension.	

Figure 5-1:FMS tests and movement aspects assessed by tests

Both the inter-rater and intersession reliability of the FMS have been evaluated and deemed high.[79,77] A score of zero to three, based on the observer's subjective analyses of movement patterns and the participant's pain experience is allocated for each of the movements. For bilateral movement patterns the lowest of left and right raw score is used to calculate a total score out of 21. Specific scoring guidelines for each movement pattern have been described by the authors of the FMS.[19] In brief, zero is allocated when the participant experience pain during performance of the movement regardless of the quality, one for inability to perform the movement, two if the movement is performed with compensation and three if the movement is performed without compensation. The authors of the FMS hypothesised that higher scores indicate lower injury risk.[19]

A score of 14 or less have been found to positively predict serious injury among American football players.[8] War fighter candidates who scored 14 or less were also twice as likely to not graduate due to injury than those with higher scores.[114] Similar findings were also documented for female college athletes,[72] military officer candidates,[84] and high school basketball athletes.[115] Low FMS scores (≤14), weaker performance in fitness tests (three mile run) and prior injury were all found to be independent predictors of injury.[88] The results of all the above mentioned studies therefore suggest that functional movement impairments, as exposed by the FMS, is an identifiable risk factor for injury among various athletes and that those athletes that score less than a certain total cut-off score (e.g. 14) are more likely to sustain an injury than those who score higher than the cut-off score.

If found to be a valid predictor of cricket pace bowler injuries, the tool will enable health and fitness professionals to identify those players at risk of sustaining in-season injuries and address the possible preventable causes in an attempt to minimise the risk of those injuries. In addition, if the predictive validity of the test is found to be high, health and conditioning professionals should consider implementing the FMS in a clinical setting as the testing procedure is more user-friendly and less time consuming than many screening procedures that are currently used. Therefore, the aim of this study was to determine if the FMS is a predictor of injuries among adolescent cricket pace bowlers.

Methodology

Study design

This was a prospective, observational, quantitative study design.

Participants

The target population (243 pace bowlers) was calculated as follows: 9 (cricket playing public high schools in the chosen geographical area) X 9 (nine male cricket teams per school) X 3 (average number of pace bowlers per team). The geographical area where schools were located was selected on the basis of convenience. As cricket is predominantly played by males and none of the nine high schools in had female cricket teams when this study was conducted, only male bowlers were included.

Information regarding the study was sent to the nine cricket playing high schools and requested that those teams who would like to volunteer send through a list of potential participants. Thirty of those participants that met the inclusion criteria (male, aged 13-18 years, injury free, pace bowlers) were randomly selected using computer generated numbers. Institutional ethical approval was obtained from the Human Research Ethics Committee (M130657) of the associated tertiary institution as well as the local Department of Education. The eligible participants and their parents willingly signed consent/assent forms and the rights of the participants were protected. All procedures were conducted in accordance with the Declaration of Helsinki.

The sample size estimation was done with the following assumptions:

- A two sided two-sample t-test was performed at 5% level of significance
- The difference between FMS mean scores for injured and not-injured bowlers is 3.0 (14 and 17).
- The standard deviation on the FMS for injured bowlers was 2-3
- The standard deviation on the FMS for non-injured bowlers was 2-2.5
- The sample size for injured bowlers was 10
- The sample size for non-injured bowlers was 20

Using the above results in a power of 72% to 95%.

These assumptions were based on the results of the study conducted by Kiesl et al. (2007).[8] The mean score for those who suffered an injury was 14.3 (2.3) and 17.4 (3.1) for those who were not injured. Thirteen participants were injured while 33 were not injured resulting in an injured: not-injured ratio of 1:2.5.[8]

On the day of the screening two participants did not attend their scheduled screening sessions due to personal and transportation problems. Another participant did not complete the FMS evaluation as he experienced 8/10 knee pain during the performance of the DS. According to the FMS guidelines,[19] when a participant experiences pain during the performance of any of the tests, the screening is ceased, the participant gets a total score of 0 and that particular area or joint has to be further assessed using the Selective Functional Movement Assessment (SFMA). The SFMA does not fall within the scope of this study. Subsequently, 27 high school pace bowlers were included in the study.

Procedures

Data was collected over five sessions as illustrated in Figure 5-1. The participants were asked to perform the seven FMS tests as well as the three clearing tests.[5] The seven sub-tests were scored by the researcher, who was blinded to the participants' injury history, according to the scoring criteria set out by the authors of the FMS. The clearing exams were scored using a dichotomous variable: yes or no. A total score (out of a possible 21) was then calculated.



Figure 5-2 Main study procedures

General information regarding the bowler (type of bowler, bowling speed, hand dominance) as well as information regarding the status, nature and prevalence of any previous injuries were included in the pre-season questionnaire. The bowling speed recorded on the questionnaire was a self-reported estimate. The monthly surveillance questionnaire was designed to collect information regarding injuries sustained during the season in terms of i) anatomical site ii) mechanism of injury iii) recurrence of injury iv) extent of the injury in terms of medical attention required and dismissal from participation. These questionnaires had been validated and used in previous studies on injuries in cricket pace bowlers.[104,105,116] Prior to submission, the researcher and/or coaches went through the questionnaires to ensure all sections were completed by the participants. Participants were required to complete the questionnaire irrespective of whether they sustained an injury or not.

An injury was defined as damage or harm of any body region, sustained while participating in a sporting activity, that resulted in loss of at least one day of training or play OR that occurred during a sporting activity that required medical attention (e.g. emergency room, physiotherapy).[9]

Data analysis

All cricket related injuries sustained (contact and non-contact injuries) were included for the purposes of this study. Contact injuries were considered to be any injury sustained due to collision with another player or object (ball, bat, wickets, boundary rope or ground), while non-contact injuries were all injuries sustained in a manner not involving contact (e.g. overuse injuries, acute ligament sprain or muscle strain).

Statistical analyses were performed on SAS Release 9.2 (SAS Institute Inc, Cary, NC, USA). All continuous variables were summarised by mean, standard deviation, median, minimum and maximum values. Categorical variables were summarised by frequency counts and percentage calculations. The differences in variables between the injured and non-injured groups were compared using a two-tailed, independent t-test. A 2x2 contingency table was constructed to illustrate the association between injuries sustained by the bowlers and a cut-off score of fourteen. Fourteen was used as a cut-off score based on the findings of previously mentioned studies that found a positive association between this score and injury incidence.[8,72,84 84]. The following statistical measures were calculated for this table: sensitivity, specificity, false positive rate, false negative rate, positive and negative predictive ratios as well as odds ratio. The Fisher's exact test was performed in order to compare the FMS scores of the injured and non-injured bowlers. Statistical significance was set at $p<0.05$.

RESULTS

Demographic information

There were no significant differences in any of the demographic (age) or anthropometric variables (height, weight and BMI) between the two groups (Table 5-1). Furthermore, only two of the bowlers evaluated were left handed. Comparisons between the injured and non-injured bowlers could be made as body composition variants were similar.

Table 5-1:Demographic information of the injured and non-injured groups of pace bowlers

	Injured (n=10)	**Non-injured (n=17)**	**t-test (p-value)**
Age (years)	16.82 (1.70)	16.44 (0.78)	0.36
Height (m)	1.84 (0.04)	1.83 (0.69)	0.83
Weight (kg)	80.09 (9.02)	77.00 (7.48)	0.33
BMI (kg/m^2)	23.76 (2.96)	22.96 (2.37)	0.43

All data presented as mean (SD)

Injury Incidence

Ten (37.1%) of the bowlers sustained injuries during the season. The body regions affected are summarised in Table 5-2. Six (46.2%) of the injuries were contact injuries while seven (53.8%) were non-contact injuries. Three of the participants sustained two separate injuries. Of these, two sustained two non-contact injuries, while the third sustained two contact injuries. Of the ten participants that sustained injuries, five sustained contact injuries and five sustained non-contact injuries. The injuries frequently occurred during fielding (57.1%) then bowling (21.1%) and batting (7.1%).

Table 5-2:Body regions where in-season injuries occurred

	Contact	Non-contact	Total
Low Back	2	4	6
Lower limb	1	2	3
Upper limb	3	0	3
Other	0	1	1
Total	**6**	**7**	**13**

Observed FMS scores

The number of participants scoring 1, 2 or 3 for each subset of the per FMS assessment is represented in Figure 5-3. The statistics for the score per test and total FMS score for the injured, non-injured and group as a whole are represented in Table 5-4. The minimum total score was 12 while the maximum was 20 (out of a possible 21). The mean score was 16.44 (2.41).

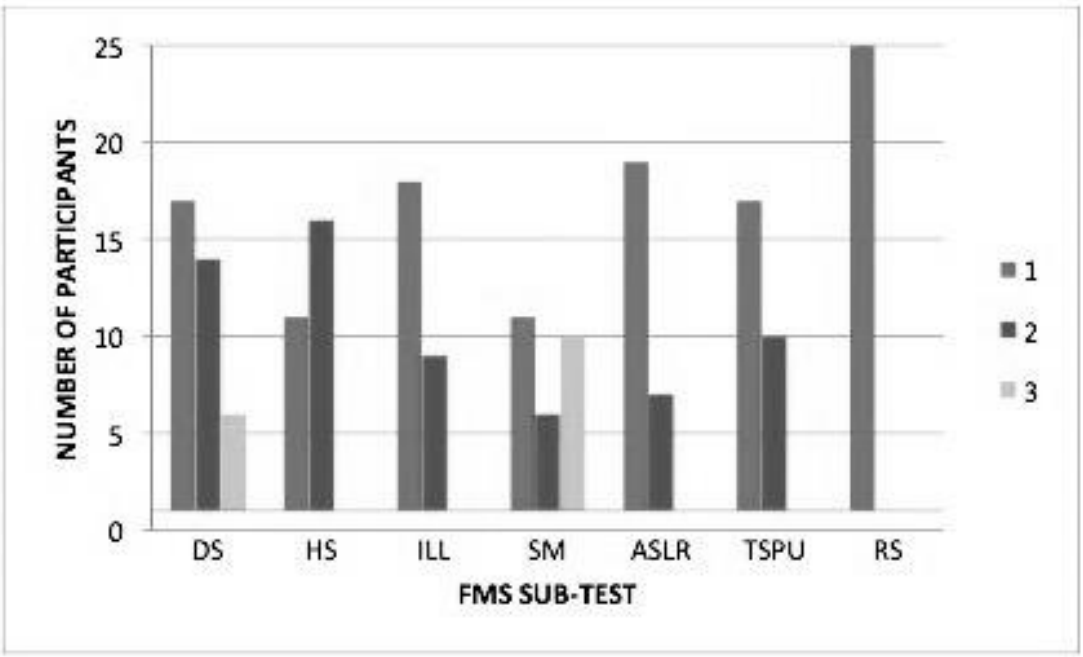


Figure 5-3: The number of participants scoring 1,2 or 3 per FMS movement (n=27).
DS= Deep squat; HS= Hurdle step; ILL= Inline lunge; SM= Shoulder Mobility; ASLR= Active Straight Leg Raise; TSPU= Trunk Stability Push-up; RS= Rotary Stability

Table 5-3:Composite and total FMS scores for injured group, non-injured group and entire group.

		Deep Squat	Hurdle step	In-line lunge	Shoulder mobility	Active straight leg raise	Trunk stability push-up	Rotary Stability	Total scores
Injured	Mean (SD)	1.83 (0.60)	2.42 (0.49)	2.58 (0.52)	1.90 (0.83)	2.60 (0.40)	2.80 (0.40)	2.00 (0.45)	16.10 (2.07)
	Median (Range)	2.00 (1-3)	2.00 (2-3)	3.00 (2-3)	2.00 (1-3)	3.00 (2-3)	3.00 (2-3)	2.00 (1-3)	17.00 (12-19)
Non-Injured	Mean (SD)	2.18 (0.73)	2.41 (0.51)	2.71 (0.47)	2.12 (0.93)	2.71 (0.59)	2.53 (0.51)	2.00 (0.00)	16.65 (2.57)
	Median (Range)	2.00 (1-3)	2.00 (2-3)	2.00 (1-3)	2.00 (1-3)	3.00 (1-3)	3.00 (2-3)	2.00 (2)	16.00 (13-20)
Contact	Mean (SD)	1.8 (0.84)	2.40 (0.55)	2.60 (0.55)	1.80 (0.84)	2.60 (0.55)	2.80 (0.45)	1.80 (0.45)	15.80 (2.17)
	Median (Range)	2.00 (1-2)	2.00 (1-2)	2.00 (1-3)	2.00 (1-3)	3.00 (2-3)	3.00 (2-3)	2.00 (1-2)	17.00 (12-17)
Non-contact	Mean (SD)	1.80 (0.84)	2.40 (0.55)	2.60 (0.55)	2.00 (1.00)	2.60 (0.55)	2.80 (0.45)	2.10 (0.45)	16.40 (2.41)
	Median (Range)	2.00 (1-3)	2.00 (2-3)	3.00 (2-3)	2.00 (1-3)	3.00 (2-3)	3.00 (2-3)	2.00 (2-3)	17.00 (13-19)
Group	Mean (SD)	2.04 (0.71)	2.41 (0.50)	2.67 (0.48)	2.04 (0.90)	2.67 (0.55)	2.63 (0.49)	2.00 (0.28)	16.44 (2.41)
	Median (Range)	2.00 (1-3)	2.00 (2-3)	3.00 (2-3)	2.00 (1-3)	3.00 (1-3)	3.00 (2-3)	2.00 (1-3)	17.00 (12-20)

There was no significant difference between the total FMS scores of the injured vs non-injured bowlers (p=0.58). The mean total score for the bowlers that sustained contact injuries was no different 15.80 (±2.17) to that of the bowlers with and non-

contact injuries at 16.40 (±2.41) (p=0.77). The number of injured and non-injured players per FMS score is represented in Figure 5-4.

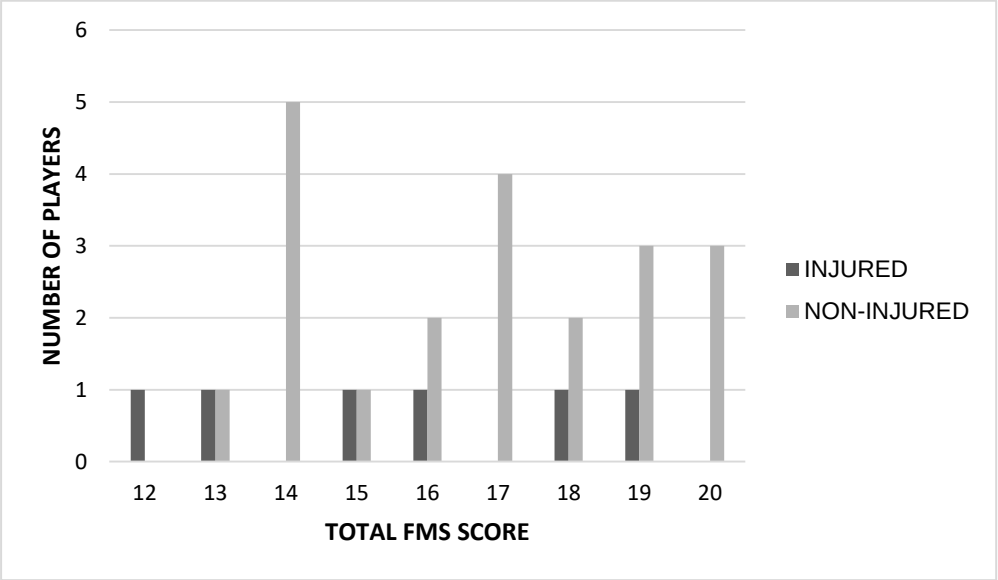


Figure 5-4: Number of injured (n=10) and non-injured (n=17) bowlers per FMS score.

A 2x2 contingency table (Table 5-4) was constructed to illustrate the number of injured and non-injured bowlers who scored ≤14 or >14. Only two (25%) of the bowlers with a score of ≤14 sustained injuries while eight bowlers (80%) with scores of >14 (even as high as 19) sustained injuries. For the purposes of determining a cut-off score, no distinction was made between contact and non-contact injuries as the non-contact injury group only represents 50% of the bowlers who sustained injuries. As previously mentioned, the cut-off score of 14 was based on findings of various authors, all who included both contact and non-contact injuries in the calculation or verification of this score.[8,72,84]

Table 5-4:2x2 Contingency table for injured and non-injured players that scored ≤14 and >14

			Not injured	Injured	
FMS Score	**Total**	**≤ 14**	6(35%)	2(20%)	8
		>14	11(65%)	8(80%)	19
Total			17	10	27

At a ≤14 cut-off score a sensitivity of 0.20 and specificity of 0.65 was calculated. The false positive rate was 22.2% and false negative rate 29.6%. The positive and negative predictive values were 25.0% and 57.9%, respectively.

The percentage injured bowlers who scored ≤14 did not differ significantly (Fisher's Exact test, p=1.000) from the percentage uninjured bowlers who scored ≤14 The odds ratio for an uninjured bowler to score ≤14 versus an injured bowler to score ≤14, was 2.18, with a 95% confidence interval of 0.24 – 6.67, indicating that uninjured bowlers were 2.18 times more likely than injured bowlers to score ≤ 14. The odds ratio is not statistically significant. The above mentioned results therefore show that a total score of ≤14 was not an accurate cut-off score for bowlers to sustain an injury. Based on sensitivity and specificity calculations for different cut-off scores, no other cut-off score to accurately predict injury could be calculated.

Discussion

The FMS was developed as a tool to screen the quality of movement and ultimately injury risk in athletes.[19] The mean total FMS score for the bowlers evaluated in this study was 16.4±2.41. Similar findings were reported in FMS studies involving American football players (16.9±3.00),[8] military officers (16.60±1.70)[84] and war fighters (16.70 ±1.80).[114] It is worth noting that a much smaller sample size (n=27) were evaluated in this study and in the study conducted by Kiesel et al. (2007)[8] (n=46), compared to that of Raleigh et al. (2010)[114] (n=934) and O'Conner et al. (2011)[84] (n=874). Despite this vast difference, the mean FMS scores were very similar ranging from 16.4-16.9. This may indicate that the mean FMS score found in our study are still representative of the scores found in other populations.

Compared to the group's total FMS scores in this study, lower mean group composite scores were reported for a mixed group of physically active individuals (15.7±1.9)[117,] a mixed group of basketball players (14.46±2.13)[115] and a variety of elite Chinese national athletes.[118] These differences may be because only males were evaluated in this study, while females were also included in the other studies mentioned. Although conflicting evidence regarding the effect of gender on total mean FMS scores exist, lower total FMS scores have been reported for both female secondary school[119] and adolescent[120] athletes when compared to males of the same age.

There was no significant difference between the FMS scores of the injured and non-injured bowlers. Warren et al. (2015)[92] similarly reported that there was no significant difference between the FMS scores of injured (14.30±2.50) and non-injured (14.10±2.40) division I college athletes. The average total score for our pace bowlers who were injured was 16.10±2.07 which is higher than total FMS scores for injured basketball (13.90-14.64),[115] injured football players (14.30±2.30)[8] and division I college athletes that participated in a variety of sports (14.30±2.50).[92] The average total score for non-injured bowlers was 16.65±2.57. This is lower than the average total score for non-injured football players (17.40±3.10)[8] but higher than non-injured college athletes (14.10±2.40).[92] The football players who were assessed by Kiesel et al. (2007)[8] were all professional players and the FMS was part of their general fitness assessment throughout the season. It was also reported that based on the fitness results corrective exercises were implemented in their conditioning programs during previous seasons. Considering the above and the training intensity of these non-injured professional footballers one would expect that they would perform better than the school boy cricketers evaluated in this study.

Kiesel et al. (2007)[8] calculated a cut-off total score of 14 as being significant. Subsequently, other studies[72, ,115,92] also refer to this study when discussing a previously identified cut-off score. This score has been found to have a significant association with injury among American football players[8], collegiate female athletes[72] and military officers[84,114]. Wieczorkowski (2010)[115] found that a score of 14.5 predicted injury among basketball players that have had no previous injury. Peate et al. (2007)[17] reported a higher FMS cut-off score of 16.

Considering the outcomes of studies that found an association between injury and a cut off score of 14 or less[8,72,118,92] one could hypothesise that the odds ratio for having a score of 14 or less would be in favour of injured athletes. Chorba et al. (2010)[72] for example found that college female athletes that scored 14 or less had a four times higher risk of sustaining an injury than those that scored more than 14. The odds ratio calculated in our study (2.18), which showed no statistically significant difference between the groups, indicates otherwise. Bowlers who scored more than 14 had a two times higher risk of sustaining an injury than those that scored 14 or less. Wieczorkowski (2010)[115] also found that if a basketball player with no previous injury scored 14.5 or less he or she had a five times higher risk of sustaining an injury but that if previous history was not taken into account there was no evident difference in FMS scores between those players that sustained injuries and those that did not. Warren et al. (2015)[92] reported that the odds of sustaining an injury are the same for those athletes that scored fourteen or less and those that scored more than 14.

Sixty-nine percent of female collegiate athletes[72] and 70% of NFL football players[8] who scored 14 and below sustained injuries. In this study only 25% of bowlers who scored 14 or below sustained injuries, which is similar to the 22% among college basketball players.[121] In both the above mentioned studies and division I college athletes screened,[22] it was found that a cut-off of 14 could not accurately predict an increased injury risk. In addition, there was no other cut-off point that maximised sensitivity and specificity.

The sensitivity and specificity for a 14 cut-off score in this study were calculated as 0.2 and 0.65 respectively. To predict injury, Kiesel et al. (2007)[8], Chorba et al. (2010)[72] and O'Connor et al. (2011)[84] reported a sensitivity of 0.54, 0.58 and 0.45 and specificity of 0.94, 0.74 and 0.71 for a cut-off score of 14 respectively. This indicates that although the sensitivity and specificity in all the above mentioned studies are higher than this current study, all agree that a cut-off score of 14 is more likely to predict no injury for those athletes that score more than 14 than predict injury for those that score 14 or less.

The differences in sensitivity and specificity values may be explained by the nature of the different sports and subsequent nature of injuries related to the sport. Football, as researched by Kiesel et al. (2007)[8] and basketball, as researched by Chorba et al.

(2010)[72] are contact orientated sports. The authors of these studies did not distinguish between contact and non-contact injuries.

It was determined that traumatic (incident specific) injuries among military officers could be predicted by a low (14 or less) FMS scores, while overuse (gradual onset) injuries were only predicted by additional participation in general sport and exercise outside the military setting.[88] The studies by Sorenson (2009)[121] and Warren et al. (2014)[92] only included non-contact (acute and overuse of nature) and this might be the reason that the results of these studies are similar. Considering all of the above, it seems that the FMS total score is a poor predictor of non-contact injuries and it is therefore doubtful if this score can predict these types of injuries among athletes, including adolescent pace bowlers.

Movement patterns, as evaluated by the FMS, are unrelated to contact unless these movement patterns can help avoid or lessen impact of contact. The total FMS scores for the bowlers who sustained contact compared to those who sustained non-contact injuries in this current study were not significantly different. Although nearly half of the injuries sustained in this study was contact of nature it should be noted that bowling, is predominantly a non-contact sport although some contact injuries (e.g. a player getting hit by the ball or diving and landing on the ground) do occur.

There was also a difference in the definition of "injury" among the studies. Kiesel et al. (2007)[8] defined injury as a serious musculoskeletal injury that kept the player from participation in training and competition for at least three weeks. In this study as well as the study by Sorenson (2009)[121] the musculoskeletal injury should have kept the players from participating in training or matches for one day or required medical attention. The difference in injury definition would have an effect on the injury incidences recorded and ultimately also the predictive validity of the FMS. Considering this, it could be derived that this score is more relevant in the prediction of serious injuries preventing the athlete from competing and training for longer periods.

In summation, the FMS was designed to identify faulty movement patterns, in terms of asymmetries and limitations that have been changed as a result of previous injury or pain. One can therefore derive that it was designed to predict non-contact injuries

as movement patterns are independent of contact. However, considering the research findings of the studies that only included non-contact injuries [121,92], the predictive validity for injury of the tool seems poor. In studies where both contact and non-contact injuries were considered, there seems to be an association between injury risk and FMS total score. One could therefore hypothesise that, in addition to other factors, correct and untainted movement patterns might help an athlete to avoid contact. For example, if a cricketer is fielding at short leg and standing in the correct squat position (Figure 5-5) awaiting delivery from the bowler, correct movement patterns may, in addition to quick reaction time, enable him to move more effectively to catch the ball as opposed to the ball hitting him causing a contusion injury. Or when diving to catch the ball, it may enable him to execute correct diving and “falling” technique correctly" to minimise impact with the ground. For this reason, both contact and non-contact injuries were included in this study. However, considering the findings it can be concluded that the FMS is not a good predictor of any injury among adolescent pace bowlers.



Figure 5-5: Fielder in squat position awaiting delivery

This study was limited to only one geographical area and only adolescent, pace bowlers were included. Results might therefore not be generalisable to other sports or adult professional cricketers in another setting. Although a power analysis was done the sample size and injury rate was small. A larger sample size would have allowed a subgroup (contact vs non-contact) analysis. Data on injury occurrence was collected retrospectively so may be subject to recall bias. A strength of this study is that a homogenous population, consisting only of adolescent cricket pace bowlers, was included. The cricket pace bowling action is an asymmetrical action which leads to

adaption of movement patterns and soft tissue morphology.[120] It is therefore important to take the nature of the sports technique and demands into account when the predictive validity of screening tools is assessed.

Conclusion

This study demonstrates that the total FMS score is a poor predictor for injury among high school cricket pace bowlers. It is therefore doubtful if the FMS is more predictive of injury among pace bowlers than existing protocols. Further studies could be conducted to determine if a specific FMS test or asymmetries in movement patterns are more predictive of injury among pace bowlers. Furthermore, research into the role of neuromuscular control and symmetry in the avoidance of contact injuries should be conducted.

Conflict of interest

None

Funding

Funding was provided by the National Physiotherapy Society.

5.2 Linking notes for Chapters 1, 2, 4,5 and 6

This section contains information to clarify the link between Chapters 1 (BACKGROUND), Chapter 2 (LITERATURE REVIEW), Chapter 4 (PAPER 2: THE FUNCTIONAL MOVEMENT SCREEN IN THE PREDICTION OF INJURY IN ADOLESCENT CRICKET PACE BOWLERS: AN OBSERVATIONAL STUDY), Chapter 5 (PAPER 2: THE FUNCTIONAL MOVEMENT SCREEN IN THE PREDICTION OF INJURY IN ADOLESCENT CRICKET PACE BOWLERS: AN OBSERVATIONAL STUDY) and Chapter 6 (PAPER 3: VALIDITY OF THE FUNCTIONAL MOVEMENT SCREEN DEEP SQUAT: OBSERVER RATING VS KINEMATIC ANALYSES). In depth discussions in findings of individual papers are in the discussion sections of each paper, while an overall discussion follows in Chapter 8.

Any screening or assessment procedure is only valuable if both the reliability and validity of the specific test and/or series of tests included in the assessment, have been established. The reliability of both the FMS and USI for measurement of abdominal muscle have been established and documented respectively in numerous studies. As Paper 1 (Chapter 4) established an association between some abdominal muscle thicknesses and injury, there might be some evidence for the predictive validity, in terms of injury, of this screening procedure.

As Paper 2 (Chapter 5) and other studies have found no association between the FMS and in-season injury among cricketers and other athletes respectively, the predictive validity thereof is questionable. Other forms of validity for the FMS should therefore also be investigated. Chapter 6 (Paper 3) addresses the final objective of this dissertation and investigated the concurrent validity of the FMS DS when observer rating was compared to objective kinematic analyses.

CHAPTER 6

6 PAPER 3: VALIDITY OF THE FUNCTIONAL MOVEMENT SCREEN DEEP SQUAT: OBSERVER RATING VS KINEMATIC ANALYSES

Martin C, Olivier B, Benjamin N, Green A. (2017). VALIDITY OF THE FUNCTIONAL MOVEMENT SCREEN DEEP SQUAT: OBSERVER RATING VS KINEMATIC ANALYSES *(Under review)*

At the time of this dissertation submission, Paper 3 was under review at the *Journal of Sport Science,* as an original article. For the purposes of this dissertation 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, although the reference style was kept similar to that of the rest of the document.

6.1 Original article

TITLE: Validity of the Functional Movement Screen Deep Squat: Observer Rating versus Kinematic Analyses

ABSTRACT

Background: The Functional Movement Screen (FMS) aims to predict an athlete's risk of sustaining an injury by systematically rating the quality of seven functional movements, including the deep squat (DS). Research related to the validity, more specifically concurrent validity, of the FMS is however scarce.

Purpose: To establish the concurrent validity of the FMS DS by comparing real-time observer rating to objective kinematic motion analysis.

Study design: Cross-sectional, observational study

Methods: Seventeen injury-free, male cricket pace bowlers between the ages of 13 and 18 years performed the FMS DS. The quality of the DS was rated based on the FMS scoring criteria. Simultaneously, the motion was captured and analysed by the Optitrack® motion capture system. Participants were grouped according to scores received (e.g. Group 3 included all participants that scored 3). Specific joint angles of groups that achieved different observer ratings were compared using the Kruskal-Wallis and Mann-Whitney-U tests. Statistical significance was set at 0.05.

Results: There were significant differences in the degree to which the femurs passed the horizontal between Group 3 and Group1 ($p=0.04$, effect size (ES)=0.61) and Group 2 and 1 ($p=0.03$, ES=0.66). The femur passed the horizontal for Groups 3 and 2, but remained above the horizontal for Group 1. There was a difference in the degree to

which the torso was kept vertical between Group 3 and 1 (p=0.02, ES=0.66) and Group 2 and 1 (p=0.02; ES=0.72). The torsos of groups 3 and 2 were significantly more upright compared to Group 1 which were flexed forward. Except for these differences there were no statistically significant differences in the biomechanics with which the groups performed the DS.

Conclusion: This study provides evidence that during the performance of the DS, differences in some kinematic aspects, highlighted by the FMS, exist between participants who achieve different observer ratings.

Clinical relevance: As the FMS displayed questionable concurrent validity in this study and several other studies, the inclusion thereof in pre-season screening regime of high school cricket teams is not recommended.

Key terms: Functional Movement Screen, deep squat, kinematic motion analyses.

BACKGROUND AND LITERATURE

The FMS is a pre-participation screening tool, designed to predict an individual's risk of sustaining an injury.[19] This tool consists of seven functional movements, including the DS, and is designed to identify compensatory movement patterns.[19] Each test is scored on a scale of 0-3 according to specific criteria. Lower FMS scores have been associated with a higher risk of sustaining injuries.[19] The FMS has established a systematic way of examining the quality of movement during the performance of the DS, which is often included in training and assessment regimes due to the whole body nature of the movement.[74] Performance on the DS test may predict performance on the total FMS score and improvement of the total FMS score is thus related to improvement of the DS score.[74] For these reasons the DS was specifically investigated in this study.

Both inter-and intra-rater reliability of the FMS and specifically the DS have been found to be high[79] but the validity thereof is questionable. Several studies have investigated varying types of validity and concluded that the FMS displays poor construct validity,[122,123] poor criterion reference validity[49] as well as poor concurrent validity.[124,125] Concurrent validity refers to "the extent to which the results of a particular test correspond to other tests previously established for the measurement of the same construct".[126] The FMS aims to predict injury, yet no association between FMS score and tests that respectively assess previous injury,[124,125] or risky movement behaviour,[82] both known risk factors to injury, have been found. Furthermore, the FMS sets out to measure efficiency of functional movement,[19] but studies investigating the relationship between the FMS score and measures of athletic performance have found no correlation.[56,127,128]

Functional assessment of movement can only be valuable if both the reliability and validity of the assessment or screening tool is established.[98] Multi-camera motion analysis is considered the gold standard in kinematic assessment.[129] The lack of validity of other measures might be one of the reasons for the growing demand for the objective quantification of kinematics during the performance of functional, occupational and sport related movements.[93]

Kinematic movement analysis has been used for 3D quantitative analysis of various joint angles in static positions and during dynamic movement. Objective motion analyses have been used to validate the observation of knee and ankle position during the performance of a single-leg mini squat[130] and dynamic knee valgus during a drop-jump landing.[131] Studies have investigated the ability of physiotherapists to visually rate knee and pelvis position during performance of the squat, single leg squat and drop jump[49,131,132] The OptiTrack® motion capture system with infrared cameras has been used to analyse gait in patients with chronic anterior cruciate ligament injury[133] as well as motion analyses of various joint movement during the dynamic cricket pace bowling action.[105] Results of studies that compared the lower cost OptiTrack® motion capture system to more expensive gold standard systems, support the application thereof for kinematic assessment of motion.[93,134] Full body motion analysis, using a ten-camera OptiTrack® system, was deemed appropriate for the analysis of the DS test included in the FMS screening.

High sensitivity and specificity values have been reported in studies where observer rating was compared to 3D analysis for knee tracking during performance of a two-legged squat.[135],[136] Conversely, significant accuracy errors have been reported when observer rating was compared to 3D findings of running and side-stepping

maneuvers.[136] It would seem that more clinically acceptable observer ratings are achieved when slower, simpler, uniplanar movements are rated compared to faster more explosive and complicated movements.[98] It should however, be noted that observers in the latter studies[98,136] were asked to rate joint angles and tracking from video playback. Real-time movement rating may have yielded different results. Therefore, in this study, real-time observer rating of the DS, a simple uniplanar movement, was compared to 2D kinematic analysis.

The aim of this study was to establish the concurrent validity of the DS task included in the FMS by comparing observer rating to kinematic joint angle measurements related to the scoring criteria.

METHODOLOGY

Sample size

Ethical approval was obtained from the Human Research Ethics Committee of the associated tertiary institution (M130657). Written informed consent was obtained from participants who were 18 years of age or from the participants and their parents if younger than 18 years. Seventeen injury free, male cricket pace bowlers between the ages of 13 and 18 were included in the study.

Instrumentation and setting

OptiTrack® motion capture system

Ten, digital, high speed OptiTrack® V100:R2 cameras (Natural Point, NaturalPoint Inc., OR, USA), lens type: 10x4.5mm M-Mount), were mounted in an indoor venue.

Kinematic data was collected at 100Hz (i.e. at 100 frames per second) using Arena software (Natural Point, Inc., OR, USA). Identification of marker trajectories, processing and analysis were performed in Matlab (Version 7.2, Mathworks, Inc., Natick USA).

Standard FMS equipment

The standard FMS equipment (1.2 m dowel 2x6 inch board) was used during the performance of the DS.

Data collection procedures

Functional Movement Screen and kinematic data capture and processing

Motion analysis data were collected to extract kinematics during the performance of the DS movement. Reflective markers were attached with double-sided adhesive tape to pre-determined sites to track movements by the cameras. The anatomical landmarks were as follows: All markers were bilateral: base of 1st and 5th metatarsals, medial and lateral malleoli of the ankles, medial and lateral epicondyle of the femur (knee), greater trochanter, anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS), acromions, elbow, wrist, knuckle of third finger and spinous processes of the vertebrae C7, T4, L1, L4, S1.[117] Landmarks were selected for their biomechanical and functional significance.[117] The marker placement is demonstrated in Figure 6.1.

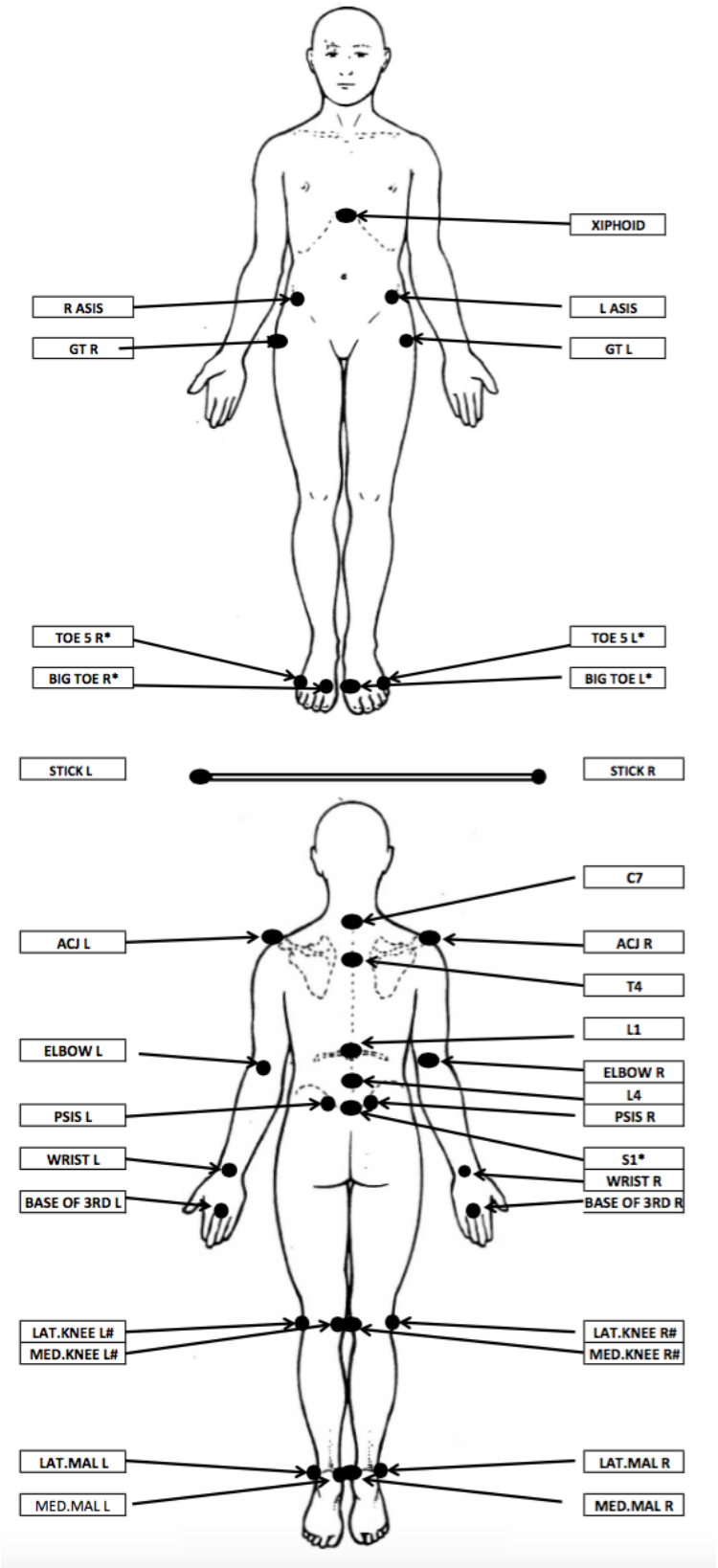


Figure 6-1:Anatomical landmarks for the placement of light reflective markers**.**

The participants were then asked to perform the DS task of the FMS at a self-selected speed, according to the standard instructions described by the authors of the FMS.[19]

Operational procedures during testing (placement of markers, giving movement instructions and monitoring on-screen tracking of the movements) were done by the researcher and assistant, who were experienced in using the FMS and motion capture system. Scoring was done by a physiotherapist experienced in the use of the FMS in daily practice. While the FMS only mentions the plane in which certain joint movements occur during the DS, it does not describe any specific position in which the observer has to position himself when viewing the movement. The position in which the physiotherapist positioned himself was therefore left up to his/her own discretion, but standard for all participants. The observer was blinded to the participants' injury history. The DS task was scored on a three-point scale [19] The standardised instructions and scoring criteria are set out in Table 6.1.

Table 6-1:Criteria and standardised instructions for overhead DS performance on the FMS[19]

INSTRUCTIONS
1. Stand tall with your feet approximately shoulder width apart and toes pointing forward 2. Grasp the dowel in both hands and place it horizontally on top of your head so your shoulders and elbows are at 90 degrees. 3. Press the dowel so that it is directly above your head. 4. While maintaining an upright torso, keeping your heels flat and the dowel in position, descend as deep as possible. 5. Hold the descended position for a count of one, then return to the starting position.
ASPECTS RELATED TO SCORING CRITERIA
1. Heels remain flat on ground (for score of 3) or board (for score of 2). 2. Upper torso is parallel with tibia or toward vertical. 3. Femur below horizontal (for score of 3 and 2). 4. Knees are aligned over feet in frontal plane. 5. Dowel remains overhead and aligned over feet.

If a participant was able to complete the DS as instructed a score of 3 was allocated. If the participant was unable to complete the DS as instructed, the 2x6 inch board was placed under the heels and they were asked to attempt the movement again. If the participant was then able to complete the movement entirely without assistance a score of 2 was given. If the participant was still unsuccessful, a score of 1 was given. Examples of the FMS DS scoring system is illustrated in Figure 6.2. Based on observer score, participants were classified into three groups i.e. those that scored 3, 2 and 1 were classified into groups labelled Group 3, Group 2 and Group 1 respectively. All

movements were performed three times. No further movement repetitions were required if a maximum score was achieved.

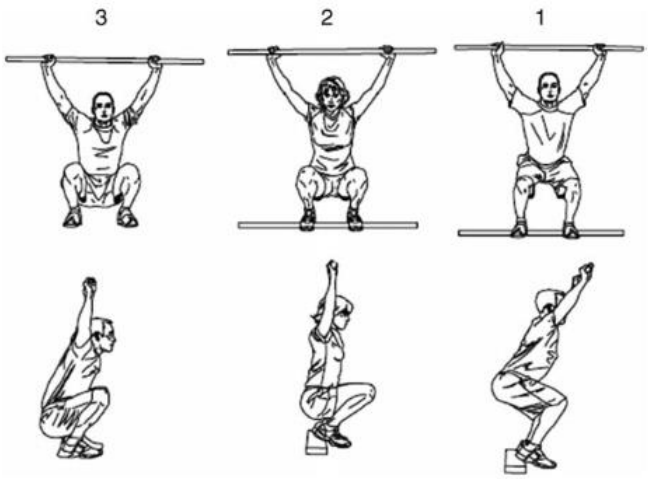


Figure 6-2:Examples of the FMS DS scoring system[76]

During the performance of the squat, three dimensional movements of the 36 body landmarks, were tracked and captured using the OptiTrack® system. Four measurements related to multiple joint positions in the sagittal plane were calculated on the left (see “Aspects related to scoring criteria” in Table 6.1). The angles were calculated as the degree of separation between the two segment planes in 3D. All angles and measurements were calculated at the deepest point of decent of the squat. Acceptable observer accuracy rating has been established when a single criterion is used to rate a single or double leg squat in the frontal plane.[130,135] In this study we focused on the accuracy of observer rating when using multiple criteria describing multi-joint movement in the sagittal plane.

Statistical analyses

Specific marker distances, joint angles and angle ratios were used to quantify each of the scoring criteria (Figure 6.3). The rationale for measurements used for each of the criteria as well as the markers used to determine measurements are summarized in

Table 6.2. All calculated ratios (i.e. torso-to-vert:tibia-to-vert ratio and dowel-to-shoulder: Dowel-to-trochanteric angle ratio) indicate the degree to which two segments are parallel to each other. A 1:1 ratio is therefore indicative of complete parallelism.

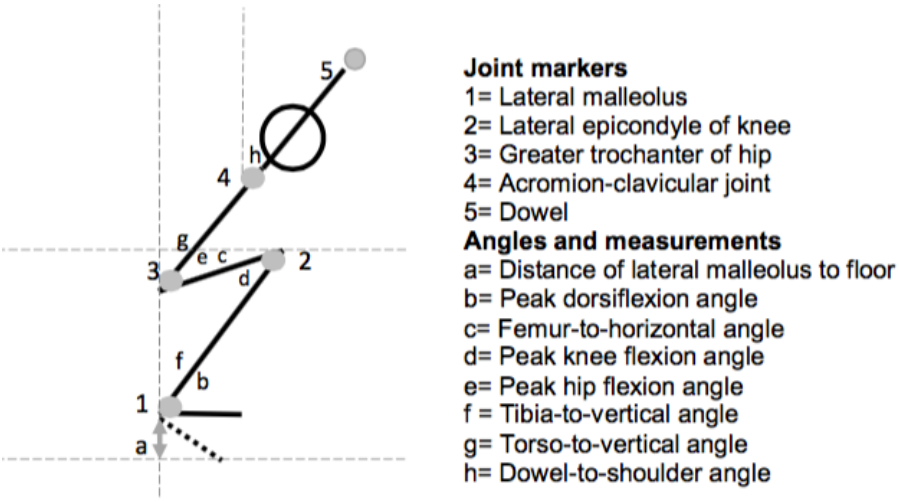


Figure 6-3:Joint markers and angles used for quantifying scoring criteria

Means and standard deviations (SD) of the kinematic measurements (joint angles and marker distance) were calculated per group.

Demographic and anthropometric data as well as kinematic measurements of the three groups as well as group pairs were compared. The Kruskal-Wallis test, with ties correction, was used for comparison of data of the three groups. The two-tailed Mann-Whitney-U test was used as post-hoc test for group pair comparisons (p-value) as well as calculation of the common language effect size (r).

Statistical significance was set at $p \leq 0.05$. Qualitative interpretation of the common language effect (r) was as follows: small effect >0.15 and <0.40; medium effect ≥0.40 and <0.75; large effect ≥0.75 and <1.10; very large effect ≥1.10 and <1.45; huge effect ≥1.45.

Table 6-2:Rationale for measurements used in the quantification of each of the criteria of the FMS DS

CRITERIA	**MEASUREMENTS USED TO QUANTIFY CRITERIA**	**RATIONAL/HYPOTHESIS**
Heels and feet remain flat on floor or board	*Relative ankle height* Distance from floor/board to lateral malleolus marker (cm)/Total standing body height (cm) x 100	As required by the scoring criteria, participants should keep heels flat on the floor or board. As the heels are raised by the board, relative ankle height for those that score 2 and 1 would increase. Relative ankle height for those that score 3 would therefore always be less than those that score 2 or 1.
	Peak dorsiflexion angle Formed by the markers on the lateral epicondyle of the knee, lateral malleolus and base of the 5th metatarsal.	During the performance of a squat where the heel is kept flat on the ground, an increase in hip and knee flexion will result in an increase in dorsiflexion at the ankle. The peak dorsiflexion angle is therefore dependent on hip and knee flexion angle. Considering the scoring criteria, it can be assumed that the knee flexion angle, and therefore also dorsiflexion angle of Group 3 and 2 would exceed that of Group 1. A distinction between Group 3 and 2 would not be so simple. In the starting position the dorsiflexion angle of Group 3 would exceed that of group 2 as the heels of group 2 is raised by the board. At the deepest point of descent this might not be the case. In both groups 3 and 2, the femur passes the horizontal BUT the board might enable a Group 2 participant to descend lower (therefore creating greater knee flexion angle and in turn greater peak dorsiflexion angle) than a Group 3 participant. As the dorsiflexion angle is so dependent on hip and knee flexion angle these measurements were not included in the results.

Femur below horizontal	*Femur-to-horizontal angle* Angle formed by the horizontal line and line between the greater trochanter and lateral epicondyle markers which represents the femur.	If the hypothetical horizontal line is set at 90°, participants that score 3 or 2 (i.e. femur below the horizontal) would have a femur-to-horizontal angle of more than 90°, whereas those that score 1 would have a femur-to-horizontal angle of less than 90°.
	Peak Knee flexion angle Angle formed by line between greater trochanter and lateral epicondyle of the knee, representing the femur, and line between lateral knee epicondyle and the lateral malleolus, representing the tibia.	The peak knee flexion angle for those that score 3 and 2, (where the femur is below the horizontal) would have a greater peak knee flexion angle compared to those that score 1 (where femur is above the horizontal).
	Peak Hip flexion angle Angle formed by line between greater trochanter and acromion clavicular joint markers, representing the torso and line between greater trochanter and lateral epicondyle markers, representing the femur.	During the performance of a squat where the heel is kept flat on the ground, hip flexion will increase as knee flexion increases.[137] The peak hip flexion angle of participants that score 3 would therefore have to be greater compared to those that score 2 or 1 and those that score 2 greater than those that score 1.
Upper torso remain parallel to the tibia or close to vertical	*Torso-to-vertical angle* Angle formed by the torso (represented by line between ACJ marker and greater trochanter) and the vertical.	If the hypothetical vertical line is set at 0°, participants that score 3 or 2 would have a smaller torso-to-vertical angle than those that score 1.
	Tibia-to-vertical: Torso-to-vertical angle ratio Ratio indicating the degree to which these two lines are parallel to each other. Tibia-to-vertical angle is the angle formed between the vertical and the line between the lateral malleolus of the ankle and lateral epicondyle of the knee, which represents the tibia.	For participants that score 3 and 2 the *tibia-to-vertical: torso-to-vertical angle ratio* should be 1:1 which would indicate that that the torso was kept parallel to the tibia.

Dowel should remain overhead	*Dowel-to-shoulder: Dowel-to-trochanteric angle ratio* Ratio indicating the degree to which the dowel-to-shoulder and dowel-to-trochanter lines remain parallel. This would give an indication if the dowel remained overhead at the deepest point of the squat. Dowel-to-shoulder angle is the angle between the vertical and the line between the markers on the dowel and ACJ. Dowel-to-trochanteric angle is the angle between the vertical and line between the markers on the dowel and greater trochanter.	In the starting position the dowel is placed overhead as per instructions given. When viewed from the side the marker on the dowel, ACJ and greater trochanter would be in a straight line or dowel-to-shoulder-angle would be slightly less than the shoulder-to-trochanter angle. If the dowel was kept in the same positon when the squat was performed without lumbar flexion (therefore for a score of 3 or 2) the *dowel-to-shoulder: dowel-to-trochanter angle ratio* would be closer to 1:1 than if the dowel was moved forward in which case the dowel-to-shoulder angle would be greater than the dowel-to-trochanter angle.

RESULTS

Demographic and Anthropometric data

Results related to demographic and anthropometric data are summarised in Table 6-3. Significant differences in height (p= 0.02) and BMI (p=0.04) between the three groups were noted. Post-hoc tests revealed that the height difference was only significant between Groups 1 and 2 (p=0.01; r=0.83) with Group 2 being, on average, 11.57 cm taller than Group 1. The BMI difference was only significant between Groups 2 and 3 (p=0.05; r= 0.56).

Kinematic measurements

Data related to kinematic measurements in the sagittal plane are summarised in Table 6.4. There were no significant differences between any of the groups in measurements related to criteria a (feet remain flat on ground or board) and d (dowel should remain overhead).

There was a significant femur-to-horizontal angle difference between the three groups (p=0.05, r =0.63). This difference was specifically between both Group 3 and group 2 compared to group 1. The mean femur-to-horizontal angle for both Group 3 and Group 2 indicates that the femur was 4.84° and 11.92° below the horizontal, respectively. The mean femur-to-horizontal angle for Group 1 was 3.41° above the horizontal. This difference was specifically between Group 3 and 1 (p=0.04; r=0.61) and Group 2 and 1 (p=0.03; r=0.66).

There was a significant difference in the mean torso-to-vertical angle between the three groups ($p=0.03$, $r=0.52$). The mean torso-to-vertical angle for Group 1 (68.32±5.36°) was greater than the means for Group 3 (58.95±4.76°) and Group 2 (58.40±2.88°). This indicates that the torso was flexed significantly more forward, away from the vertical, for Group 1 than for Groups 3 and 2. Although the torso-to-vertical: Torso-to-tibia angle ratio (the ratio used to establish the degree to which the torso remains parallel to the tibia) between the three groups was not statistically significant, this ratio was larger for Group 1 (2.61 ± 1.91) further indicating that the torsos were less parallel to the tibia than Group 3 (0.92±0.01) and 2 (0.82 ±0.01). It is noteworthy that the mean torso-to-vertical angle for Group 3 (58.95±4.76°) and Group 2 were very similar (58.40 ±2.88°), and the torso-to-vertical: torso-to-tibia angle ratio for Group 3 (0.92±0.10) indicates that torsos of these participants were more parallel to the tibia than those of Group 2 (0.82±0.10). The above results therefore show that the torsos of participants in Groups 3 and 2 were more towards the vertical than those of Group 1 but that the torsos of Group 3 were more parallel to the tibia than Group 2 and the torsos of Group 2 more parallel to the tibia than Group 1. This indicates, there are differences in the degree to which the torso remains upright and parallel to the tibia between groups.

Table 6-3:Demographic and Anthropometric comparisons between groups

					Mann-Whitney-U		
				Kruskal-Wallis	Group 3 vs Group 2	Group 3 vs Group 1	Group 2 vs Group 1
Variable	**Group 3 (n=6)** Mean (SD)	**Group 2 (n=6)** Mean (SD)	**Group 1 (n=5)** Mean (SD)	**p-value**	**p-value (r)**	**p-value (r)**	**p-value (r)**
Age (years)	16.67 (1.03)	16.50 (0.55)	16.40 (1.14)	0.84	0.6 (0.15)	0.64 (0.14)	0.77 (0.08)
Height (cm)	183.00 (4.69)	189.97 (4.97)	178.40 (4.93)	0.02*	0.06 (0.54)	0.27 (0.33)	0.01* (0.83)
Weight (kg)	79.50 (8.09)	72.67 (5.35)	82.60 (9.40)	0.13	0.15 (0.42)	0.46 (0.22)	0.07 (0.55)
BMI (kg/m^2)	23.70 (1.83)	21.84 (3.31)	25.89 (2.03)	0.04*	0.05* (0.56)	0.07 (0.55)	0.07 (0.56)

*statistically significant ($p \leq 0.05$)

Table 6-4:Kinematic measurements for quantification of criteria

MEASUREMENT	GROUP 3	GROUP2	GROUP1	Kruskal-Wallis	Mann-Whitney-U		
					Group 3 vs Group 2	Group 3 vs Group 1	Group 2 vs Group 1
	Mean (SD)	Mean (SD)	Mean (SD)	p-value	p-value (r)	p-value (r)	p-value (r)
HEELS REMAIN FLAT ON GROUND							
Relative ankle height (%)	5.06 (0.42)	5.35 (1.00)	6.28 (1.95)	0.72	0.69 (0.12)	0.47 (0.22)	0.58 (0.17)
FEMUR BELOW HORIZONTAL							
Femur-to-horizontal(°)	94.84 (17.73)	101.92 (9.55)	86.59 (7.27)	0.05*	0.63 (0.14)	0.04* (0.61)	0.03* (0.66)
Peak knee flexion (°)	150.83 (22.88)	130.40 (27.80)	125.80 (36.87)	0.40	0.35 (0.27)	0.14 (0.45)	0.58 (0.16)
Peak hip flexion (°)	155.04 (10.95)	137.33 (52.35)	143.02 (10.72)	0.23	0.75 (0.09)	0.14 (0.44)	0.14 (0.44)
TORSO REMAIN PARALLEL TO TIBIA OR TOWARD VERTICAL							
Torso-to-vertical (°)	58.95 (4.76)	58.40(2.88)	68.32(5.36)	0.03*	0.52 (0.18)	0.02* (0.66)	0.02* (0.72)
Tibia-to-vertical: Torso-to-vertical angle (ratio)	0.92 (0.10)	0.82(0.10)	1.15(0.38)	0.19	0.11 (0.46)	0.11 (0.72)	0.14 (0.44)
DOWEL REMAIN OVERHEAD AND IN LINE WITH FEET							
Dowel-to-shoulder: Dowel-to-trochanter angle (ratio)	0.92 (0.39)	0.56 (0.1)	2.61 (1.91)	0.40	0.37 (0.20)	0.46 (0.22)	0.28 (0.36)

*statistically significant (p≤0.05); ° - degree

DISCUSSION

The developers of the FMS suggest that specific mechanics related to the squat differ between the levels of scoring as determined by the FMS.[76] In this study, we set out to determine if the suggested kinematic differences are valid by comparing real-time observer score (based on the FMS scoring criteria) to kinematically measured joint angles.

Demographic and Anthropometric data

There were significant differences in height and BMI between the three groups. More specifically, Group 2 was significantly taller than Group 1 ($p=0.01$) and the BMI for Group 3 was higher than Group 2 ($p=0.05$). These findings are supported by large and medium (0.56) effect sizes. Pubertal development occurs between the ages of 13-16 years and is characterised by change in body composition and rapid skeletal growth. During this time, rate of skeletal development exceeds that of muscular development.[138] This skeletal-muscular growth rate imbalance has an effect on how the levers of the body are moved during the execution of functional movement skills. Adolescent males where maturation of the muscular system has matched that of skeletal maturation, could therefore execute the same movement differently than males where larger skeletal-muscular system imbalances exist. This could explain the difference in manner of execution, and therefore scoring, of the DS between the two groups.

The BMI for the Group 3 was significantly higher than that of Group 2. The mean BMI

scores for both groups were still considered within normal ranges (17.2-24.7 kg.m^2) for the mean age of both groups.[139] BMI and waist circumference are significant predictors of fundamental movement skills such as running and jumping where participants with lower BMI scores perform better.[140] This difference might occur because of the nature of the fundamental movement skills tested. The DS is less dynamic in nature compared to the skills (running, jumping, throwing, etc.) evaluated by Okeley et al. (2004).[140] Although comparisons with Group 1 did not yield any significant differences, it should be noted that Group 1 (i.e. group with the lowest score) had the highest mean BMI and that this BMI score did not fall within the previously mentioned normal range.

Kinematic measurements

In this study comparison of the objectively measured joint angles indicates that, at the deepest point of squat descent, there were no statistically significant differences with regard to the positon of the ankle or overhead position of the dowel between the three groups. These findings were supported by small and medium effect sizes.

The relative ankle height for Group 1 exceeded that of Group 2 which exceeded that of Group 3. These statistically insignificant differences might be due to chance but a difference in ankle height between the groups was expected, as the placement of the 2x6 inch board under the heels of the participant raises the height of the malleolus from the ground. Even though this raised height might not be statistically significant, the fact that the participant required the assistance of the board to complete the movement is clearly visible to the observer. A distinction between those that score

three and those that score two or one is therefore simple. However, a distinction between those participants that score two and one, i.e. those that keep their heel flat on the board and those that might raise their heels off the board might not be as obvious to the naked eye. In this study, even though there was no statistical difference in the calculated relative ankle height between Group 2 and Group 1, the participants were still rated differently by the observer.

As hypothesized, the femur-to-horizontal angle for Group 3 and Group 2 was below the horizontal, while that of Group 1 was above the horizontal. The suggestion by the authors[19] of the FMS that those who score higher would be able to squat deeper while maintaining flat heels, either on the ground or board, and that an observer would be able accurately rate the quality of the movement based on this specific aspect, is supported by this finding.

Individuals who score differently on the FMS DS exhibit different lower limb mechanics.[141] More specifically, in the above mentioned study there was no difference in peak knee and hip flexion angle between the groups . Considering, that the scoring criteria of the FMS is based on the premise that the quality of a movement would be due to differences in kinematics one would expect differences in joint angles of especially the lower extremities. Furthermore, in a closed chain, knee flexion would increase as the hip flexion increases.[137] During the performance of the squat one would expect that when a participant performs a DS in such a manner that the femur passes the horizontal, knee and hip flexion would be greater compared to that of a participant where the femur does not pass the horizontal unless that participant uses other compensatory movement strategies. In this study, even though there were significant differences in femur-to-horizontal angles between Group 3 and 1 and Group

2 and 1 there were no difference in hip and knee flexion angles. This might indicate that other compensatory movement strategies not specifically addressed in the FMS scoring criteria might be utilised by participants to gain depth during the DS.

The scoring criteria states that for a score of 3 or 2 the upper torso should be toward the vertical or parallel with the tibia during the squat. The torso-to-vertical angle of Group 3 and Group 2 was significantly more toward the vertical when compared to that of Group 1. The finding therefore suggests that, in accordance with the scoring criteria, there was no significant difference between Group 3 and 2 when considering the degree to which the trunk is kept toward the vertical but that Group 1 flexed the trunk significantly more forward. Considering the scoring criteria, one would expect that the degree to which the torso is kept parallel to the tibia for Group 3 and 2 would be significantly more (i.e. the torso-to-vertical: tibia-to-vertical ratio closer to 1) than for Group 1. There was no significant difference in torso-to-vertical: tibia-to-vertical angle ratio between the three groups. The large effect size (0.72), but insignificant difference, of this ratio between Group 3 and Group 1 but not Group 2 and 1 (0.44) should be noted. It would seem that the degree to which the trunk moves away from the vertical has a greater effect on the observer's score than the degree to which the torso is kept parallel to the tibia.

Various authors explored levels of agreement between human visual and objective 2D or 3D motion analysis when assessing a single[130,135] and two-leg squat.[135] Even though both studies found clinically acceptable results, in terms of accuracy of observer rating, observers only had to base their rating on a single criterion: whether the knee travelled medial to the second toe in the frontal plane. The FMS requires the observer to score the DS based on joint movement in both the frontal and sagittal

planes, but does not describe a standard position in which the observer should position themselves when scoring the DS or any of the movements included in the FMS. Furthermore, the FMS scoring criteria requires the observer to simultaneously consider multiple joint movements when rating the quality of the DS, which can be challenging for the observer.

CONCLUSION

This study provides evidence that during the performance of the DS, kinematic differences exist between participants that are rated differently. However, not all of these differences, as described in the FMS scoring criteria and perceived by the observer are supported by objective kinematic analysis. The concurrent validity of the overall observer rating for the DS is therefore questionable. Further research should investigate the validity of observer rating of other movements included in the FMS. Additionally, the influence of anthropometric measurements, specifically height and BMI, on performance of the FMS should be investigated. The results should be interpreted with caution as a Type II error may have occurred and a significant effect could have been missed due to the small sample size. However, to compensate for a possible type II error, effect sizes were also calculated

6.2 Additional notes for Chapter 6

This section contains additional information that the researcher deemed relevant but due to word count restriction could not include in Paper 6. More specifically, the discussion regarding possible reasons for the significant difference in height between the three groups and scoring criteria related to the torso is elaborated on.

Additional discussion regarding significant height difference

As mentioned in the results, Group 2 (those who scored 2 out of 3) was significantly taller than Group 1 (those who scored 1 out of 3) ($p=0.01$, $r=0.83$). Another factor explaining the difference in DS score of these groups with significant height differences, might be related to the effect geometric proportion has on perceived joint motion. With his Vitruvian man, Da Vinci described the geometric proportions of the human body.[142] He further describes how limbs that are longer have different geometric shape and length and the way movements are executed might therefore appear different to the naked eye, when they are actually very similar to those of participants with shorter limbs.[142]

Scoring criteria related to the torso angle.

As described in the introduction of Paper 3 (Table 3.1), one of the scoring criteria states that the DS should be performed with the upper torso parallel to the tibia OR toward the vertical. The fact that this criterion mentions two possible positions for the upper torso angle (either exactly vertical OR parallel to the tibia) may lead to confusion for the observer. If the torso remains upright toward the vertical it is simple for the naked eye to identify a deviation away from the vertical. Conversely, if the torso is parallel to the tibia, it is moved forward away from the vertical. To judge the degree to which it exceeds the line parallel to the tibia becomes difficult to judge with the naked eye.

6.3 Linking notes for Chapter 6

This section contains information to clarify the link between Chapters 1, 2, 4 and 6. In depth discussions of findings of individual papers are in the discussion sections of

each paper, while an overall discussion follows in Chapter 8.

FMS has gained popularity due to the screening tool's simplicity and user-friendliness. The first (Paper 1) and last objectives (Paper 3) of this dissertation were to investigate aspects related to the validity of the FMS in terms of injury prediction and observer rating. Even though the aim of the FMS is to identify faulty functional movement patterns, a risk factor for injury, the findings of Paper 1 and other studies referenced in Chapter 4, place doubt on the predictive validity thereof. As the value of the FMS score is determined by the accuracy of the observations of the rater, the validity of the raters score, based on the scoring criteria, is of the utmost importance. The findings reported in Paper 3 (Chapter 6) make the concurrent validity of observer rating questionable. Based on the findings of both Papers 1 and 3 the use of the FMS as a pre-season screening tool for adolescent pace bowlers is not recommended.

CHAPTER 7

7 RESULTS

7.1 Introduction

Only pertinent data and analyses from the pre-season and injury surveillance questionnaires were included in Papers 1 and 2. Results, related to the pre-, in-, and post-season questionnaires not specifically included in the respective papers are summarised in this chapter under the following headings.

7.2 Injury Incidence surveillance

7.2.1 Pre-season surveillance

7.2.2 In-season surveillance

7.2.3 Post-season surveillance

Results specifically related to the association of abdominal wall muscle morphology as measured by USI and in-season injuries is described in Paper 1 (Chapter 4, p40).

Results specifically related to the association of pre-season FMS scores and in-season injuries is described in Paper 2 (Chapter 5, p61).

Results specifically related to the concurrent validity of the FMS DS is described in Paper 3 (Chapter 6, p82).

7.2 Injury Incidence surveillance

7.2.1 Pre-season surveillance

The pre-season surveillance questionnaire revealed that of the 28 bowlers evaluated, fifteen bowled at a speed of 101-105km/h, six at 120-130 km/h and seven at more than 135km/h. Twenty six were right handed, while two were left handed. Six of the bowlers were opening bowlers, eight first change, six second change, four third change and four other position bowlers. Sixteen of the bowlers had been bowling for

more than more than six years, three between four and six years, two between one and three years and four for less than one year.

21 of the bowlers had no injury at the time of completion of the pre-season questionnaire while seven suffered from injuries. Twenty participants had previously suffered a total of sixty-nine injuries while eight participants had not suffered any previous injury. The body regions where bowlers suffered previous injury are as follows: elbow (4.4%), hip (8.9%), knee (17,8%), lower back (24.5 %), shoulder (17.8%), sternum/ribs (13.3%) and wrist (13.3%). 69% of the injuries were non- contact and 31% contact injuries. The number of weeks the bowlers was unable to train and number of matches missed are summarised in Figure 7-1 and 7-2 respectively.

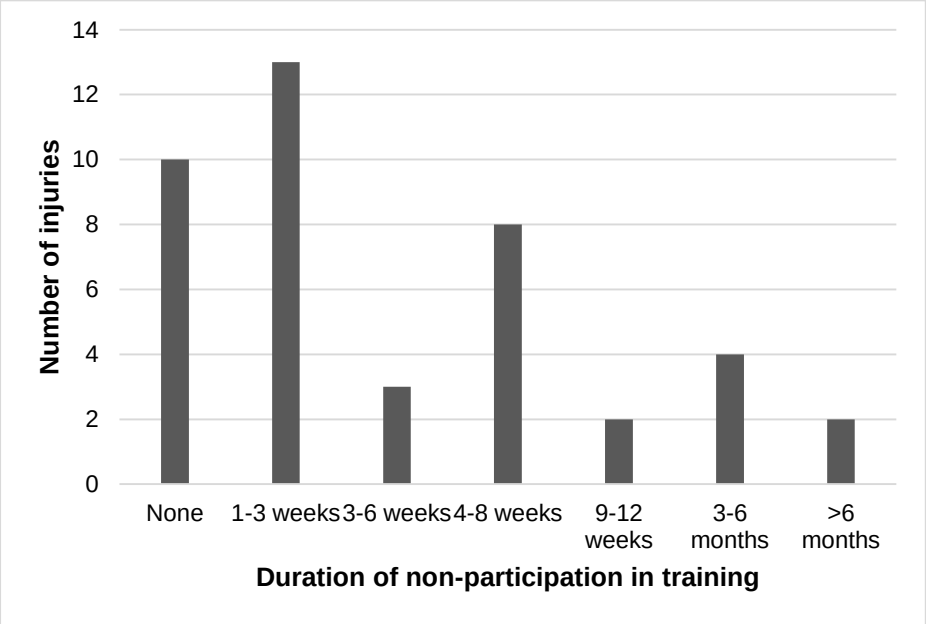


Figure 7-1:Pre-season non-participation in training due to injury

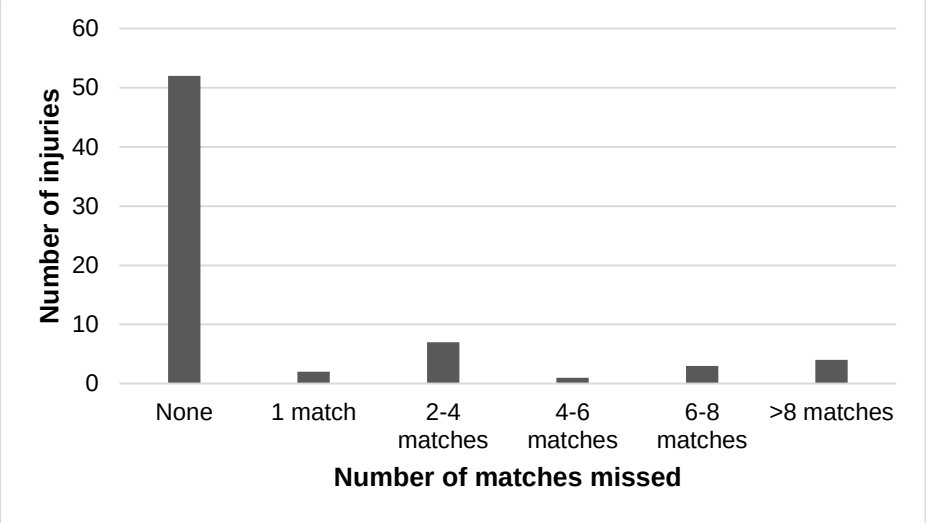


Figure 7-2: Pre-season non-participation in matches due to injury

The majority (38.1%) of these injuries occurred in the first two months on the season, 28.57% in the middle two months, 11.9% in the last two months and 21.43% outside the season. Most of these injuries were managed with physiotherapy or a combination of physiotherapy and strapping, rest and medication (63.42%), 9.76% did not receive any treatment, 12.2% were managed with strapping and/or a brace, 9.76% were surgically treated and 4.88% with rest with or without immobilisation.

The bowlers felt that these injuries could have been prevented with adequate warm-up and cool down (50%), then by stretching (26.67%), adequate training (13.33%), wearing protective gear (6.67%) and other means (3.33%).

7.2.2 In-season injury surveillance

During the season a total of 39,7% of the bowlers sustained injuries. Eight players (28.6%) reported that they had sustained injuries during month one and four players (14,3%) during month two of surveillance. One player sustained injuries in month one and two. The body regions where the injuries occurred are summarized in Table 7-1.

Table 7-1: Body regions where in-season injuries occurred

	Month 1	Month 2	Total
Upper limb	3	0	3 (21.43%)
Lower limb	2	1	3 (21.43%)
Lower back	4	2	6 (42.86%)
Other	1	1	2 (14..29%)
Total	**10**	**4**	**14**

At the time of the injuries were sustained bowlers rated the pain between six and nine out of ten and at time of completion of the pre-season questionnaires pain was mostly (64.3% of bowlers) rated between zero and four. The rest of the bowlers rated their pain between five and nine out of ten (35.7%).

Six (42.86%) of the injuries were contact injuries while eight (57.14%) were non-contact of nature. (NOTE: One of the bowlers that sustained an injury was not included in the FMS study (Paper 1). This participant experienced ankle pain during the performance of the DS and the remaining FMS tests were therefore not completed. The participant was still considered for the USI study (Paper 2) and his in-season injuries monitored. For this reason the FMS study reports six contact injuries and seven, not eight, non-contact injuries). The majority of the injuries occurred during fielding (35.7%) then bowling (28.6%) and batting (14.3%). 42.9% of injuries occurred during training, 42.9% occurred during matches and 14.2% during other incidences. Non-participation in training and matches as a result of in-season injuries are depicted in Table 7-2 and 7-3 respectively.

Table 7-2: In-season non-participation in training due to injury

Duration of non-participation	Number of training sessions missed
None	2 (14.2%)
<1 week	6 (42.9%)
1-3 weeks	6 (42.9%)
Total	**14**

Table 7-3: In-season non-participation in matches missed due to injury

Number of matches missed	Number of matches missed
None	9 (64.3%)
1	1 (7.1%)
2-4	2 (14.2%)
5-6	1 (14.2%)
>8	1 (14.2%)
Total	**14**

With the exception of one, all of the injuries were managed with physiotherapy only or physiotherapy in combination with strapping and no other treatment. Seven of the reported injuries had not occurred previously while five injuries were recurring.

The players felt that four injuries could not have been prevented while eight could have been prevented with a combination of adequate training, warm-up, cool-down and stretching.

7.2.3 Post- season injuries

Post-season 25 bowlers were injury free while 3 were suffering from injury. All of the players reported that improvement of performance were very important while 26 players felt that injury prevention was very important and two that injury prevention was not so important.

18 of the 28 players had also trained 2-4 times per week outside of cricket practice during the past-season. This training involved running (31.58%), weight-training and running (5.26%) and other sports (63.16%).

Seventeen of the bowlers felt that injuries sustained during the season could have been prevented with a combination of one or more of the following, protective gear, adequate training, warm-up, cool-down and stretching.

CHAPTER 8

8 DISCUSSION

In Chapter 8 an overall discussion of the implications and significance of Chapter 5 to 7 (Paper 1-3) in light of the literature in Chapter 2 is presented. In Chapter 4 and 5, two original papers investigated the association between intrinsic factors (i.e. qualify of functional movement patterns and morphometry of the lateral abdominal wall muscles) and injury. Paper 1 found an association between IO symmetry as well as TA activation and injury. Paper 2 found no difference in the total FMS score between injured and non-injured bowlers and it was therefore concluded that there was no association between the movement patterns tested by the FMS and injury.

The next paper, Paper 3, compared observer rating of the FMS overhead DS to kinematic analysis of the DS. While rating of some of the criteria were comparable to kinematic analysis of the DS, others were not and the concurrent validity of the FMS DS is therefore questionable.

The discussion in Chapter 8 will firstly discuss the injury incidence results of this study. The rest of the Chapter will revolve around the importance of the use of valid, reliable screening procedures.

This discussion will be presented under the following subheadings:

8.1 Pre- and in-season injury incidence among adolescent pace bowlers

8.2 Screening tools for predicting contact and non-contact injuries

8.3 The use of valid, reliable and user-friendly tests

- 8.3.1 The validity, reliability and user-friendliness of USI
- 8.3.2 The validity, reliability and user-friendliness of the FMS
- 8.3.3 The use of FMS screening in conjunction with other screening procedures in the prediction of injuries
- 8.3.4 The use of FMS in the prediction of contact injuries

More detailed and focussed discussion sections can be found in the discussion section of each respective paper.

8.1 Pre- and in-season injury incidence among adolescent pace bowlers

Injury surveillance is fundamental to prevent and reduce the risk of injury. This study yielded similar results to what was found in the literature with 35.7% of the cricketers sustaining injuries over the surveillance period. Milson et al. (2005)[24] found that 34.2% of 196 elite South African school boy cricketers sustained injuries during the 2003/2004 cricket season. Stretch (2014)[7] surveyed under 15,17 and 18 year old elite school boy cricketers over five years and reported that 29-36%, depending on the age group, sustained injuries. Although findings from this study are comparable to the above, our injury levels are lower than the results Stretch (1995)[143] reported for provincial and club level cricketers. This is most likely because the number of games and training sessions at club and provincial level is much higher than at school boy level.

Among the pace bowlers surveyed in this study lower back injuries (50%) were the most common area of injury. This rate is higher than the 33% reported by Stretch (2014).[7] It is also higher than the lower back injury incidence for South African provincial and club level players (33%) and for international players from South Africa, England and Australian (18-23%).[22] In this study 21.4% of the cricketers sustained lower limb injuries while Stretch (2014)[7] reported 38% and Stretch et al. (2012)[22] 46% lower limb injuries among elite school boy cricketers. The differences in the above mentioned injury percentage may be because this study only surveyed pace bowlers while all the other mentioned studies took all cricketers into account. Lower back injury is one of the most common types of injury sustained by cricket pace bowlers.[43] Pace bowlers have been known to suffer more trunk and lower back injuries at any given time due to the nature of the bowling action.[44] The results of the study conducted by Gregory et al.(2002)[35] agree with the above. They reported a lower back pain prevalence among pace bowlers of 75.6% compared to 48.1% in spin bowlers. Furthermore, all of the participants were adolescents still going through their growing phase. In addition to other factors, structural abnormalities that can occur at an early age can be aggravated by the trunk rotation associated with a mixed bowling action.[22] Adolescent bowlers are therefore

predisposed to back injuries which can be compounded through excessive bowling during the growth period when the spine is relatively immature.[22]

Just over 1/5 (21.4%) of the cricketers in our study sustained upper limb injuries. This is similar to the results reported by Stretch (2014)[7] (26%), Stretch et al.(2012)[22] (23-29%) and Stretch (1995)[143] (23%). This provides further support for the inclusion of any body part in the definition of injury even though lower back injuries are preferentially investigated among pace bowlers.

In contrast to other studies, the largest group of injuries occurred while fielding (35.7%). Other studies concluded that 23[143]- 33%[7] of injuries occurred during fielding. Other studies have found that bowling was the primary mechanism of injury and accounted for 40-50.7% of injuries.[7,22,143,24] This study found that bowling accounted for second most number of injuries (28.6%). The difference in these findings might be because all participants in this study were bowlers. Their training and conditioning might therefore be aimed more toward bowling and not fielding leaving them more prone to sustain an injury when fielding.

In this study equally as many injuries occurred during matches as during training (42.9%) while 14.2% occurred during other activities. Similarly, Stretch (1995)[143] found that among senior provincial and club cricketers, most injuries occurred during training (47%) and then matches (45%). Stretch (2014)[7] and Stretch et al. (2012)[22] found that most of the injuries among elite school boy cricketers occurred during matches (30-31%), then training (27-29%). Although the match/training injury incidence in very similar in this and all mentioned studies, the differences in training and match injury incidence might be because of the following reasons. The intensity of physical activity in a match situation is much higher than in training increasing the risk of sustaining an injury in a match. The injury incidence in training might be higher because the time spent in training is usually much higher than match time, the opportunity to sustain an injury during training might therefore be higher.

The majority of injuries (64.3%) did not result in bowlers missing any matches and none of the injuries resulted in non-participation for training for more than three weeks. Considering that only two of the participants were eighteen years of age, these results

were similar to the findings of Stretch (2014)[7]. He reported that injuries (51%) sustained by u/18 cricketers resulted in them being out of the game for longer periods (more than 8 days) while younger players (u/15, u/16) were only kept out of the game for 1-7 days.

8.2 Screening tools for predicting contact and non-contact injuries

In cricket as well as other sports, acute injuries occur as a result of either contact or non-contact mechanisms. Although the distinction between the two is well understood all potential mechanisms are less clear.[144] Risk factors for sustaining injuries are multifactorial and include both internal and external risk factors. Research related to the design of algorithms that consider multiple known injury risk factors in an attempt to quantify an athlete's risk of sustaining an injury is scarce. Fickling (2014)[145] designed an algorithm for the prediction of non-contact ACL injuries, while Lehr (2015)[146] attempted to do the same for non-contact lower extremity injuries.

Due to the external mechanisms involved in contact injuries the design of algorithms predicting these injuries are more complicated. This might partly be because the modifiability of the tools is subject to many uncontrollable external factors. For example, many sporting bodies have attempted to protect athletes by implementing or adapting stringent rules of the game. For instance, Law 10(4) of the IRB rugby union rules[147] states that "A player must not tackle (or try to tackle) an opponent above the line of the shoulders even if the tackle starts below the line of the shoulders. A tackle around the opponent's neck or head is dangerous play." Whether a player abides by this rule is less controllable. Similarly, the International Cricket Council (ICC) and American National Football League (NFL), enforce the on-field wear of protective gear in an attempt to protect players. However, the gear should still allow for freedom of movement which might leave some body parts exposed and therefore susceptible to contact injury. For these reasons research should focus on the extent to which intrinsic risk factors, that are inherently more modifiable, influence the risk of an athlete sustaining a contact injury. This study therefore attempted to investigate the role of intrinsic risk factors in both contact and non-contact injuries.

8.3 The use of valid, reliable and user-friendly tests

The availability of valid, reliable and user-friendly screening tests that could be used by everyday sports health practitioners is limited. Screening tests identify asymptomatic individuals who may be at risk of sustaining an injury. Practically, the ability to classify individuals in the correct risk category (i.e. high or low risk of sustaining an injury) depends on the accuracy of the screening test. Traditional pre-season screening regimes, like those implemented by the South African Rugby Union[148] and South African Cricket Council contain a vast number of tests. Furthermore, the ability of these traditional screenings to quantify injury risk is unconfirmed.

8.3.1 The validity, reliability and user-friendliness of USI

Although the cost of USI equipment is significantly higher than that of the FMS, the procedure is fairly simple. While the reliability of the USI procedure has been well documented (see Chapter 2 (Paper 1), studies investigating the role of these muscles and their association with injury risk have had conflicting results (see discussion of Paper 2). While adaptations resulting from the nature of the pace bowling action including preferential asymmetrical hypertrophy of IO, EO and TA[43] may affect risk of injury[40] they may also serve as a protective mechanism as is shown in Chapter 4 (Paper 1). Considering these conflicting results, as well as those related to the role of TA in injury prevention of pace bowlers, the testing procedure might be subject to scrutiny.

One of the reasons for conflicting results might be related to the position of the participant during the USI procedure. When resting and activated muscle thickness images are captured for analysis it is done so with the participant in a supine, non-weight bearing position. During the performance of all activities related to the game of cricket and especially bowling, athletes are in an upright bipedal or unipedal weight-bearing position. Furthermore, USI testing is static in nature while the bowling action and other athletic skills associated with cricket are dynamic. Electromyographic recordings in six healthy individuals revealed that in all subjects the activity of both the internal and the external oblique muscles was significantly higher in unconstrained standing than in a supine posture.[149] The principle of dynamic correspondence as described by Verkhoshansky & Siff (2009)[150] states that because a muscle or muscle

chain is effective in one posture, does not mean that it will translate to correct technique or activation in a different posture.

While Hides et al. (2016)[71] observed and trained activation of abdominal musculature of cricketers with LBP under simulated weight bearing positions, the weight loaded was only 25% of the total body weight of the participants. As shown in the literature review (Chapter 2) during front and back foot strike the ground reaction forces that have to be endured are two to five times that of body weight. So regardless of the fact that the findings of this study show a change in muscle activation pattern, translation of these patterns to the field is doubtful.

While capturing an US image of the lateral abdominal wall during the performance of a dynamic action is practically impossible, capture and analysis of these muscle thicknesses in a standing or more functional posture might be more relevant to injury risk associated with the same or similar posture.

8.3.2 The validity, reliability and user-friendliness of the FMS

As altered movement patterns have been established as an injury risk factor, movement screening is often incorporated in the clinical field and has become a popular research topic.[144] The costly nature of sophisticated research equipment such as high speed motion analysis is a barrier for many clinicians and for this reason more cost and clinician friendly, field-based movement screening tools have been developed and implemented in clinical settings. In addition to the FMS, these tests include the Star Excursion Balance Test,[104] the Y Balance Test, the Drop Jump Screening Test, the Landing Error Scoring System, and the Tuck Jump Analysis.[144]

Due to the user-friendly, cost and time effective nature of the FMS and the fact that the testing does not require expensive equipment, this tool has become popular in fitness, sport and rehab settings.[151] While the majority of studies agree on good to excellent intra-and interrater reliability of the test,[152] there are many conflicting results regarding the validity of the FMS to predict injury.

Construct validity of the FMS

Since the commencement of this study, several systematic reviews have summarised findings of FMS related research and published conclusions related to the predictive validity of the FMS. A systematic review by Kulju et al. (2015)[151] found that although the FMS appears to highlight limitations and asymmetries in some movement patterns it is not a valid measure to predict athletic performance. Another review [152] concluded that the ability of the FMS total score to predict injury is only supported by moderate scientific evidence. A third systematic review and meta-analysis[153] suggested that while the FMS studies might have questionable study designs, the FMS provides a level of discriminatory evidence only slightly above chance. The meta-analyses of this study indicated that, like the findings in paper 2, specificity (85.70%) of the FMS exceeds the sensitivity (24.70%) thereof. This indicates that the FMS is more likely to identify those individuals that have a lower risk of sustaining an injury (high FMS score) than those with a high risk of injury. Reasons, other than differences in study design, for the conflicting findings regarding the predictive validity of the FMS, might be related to other forms of validity.

Construct validity of movement patterns is related to the degree to which the movement patterns included in the FMS actually simulate those relevant to basic athletic (running, jumping etc.) and sport specific movements.[154] Consider the DS for example, where participants are encouraged to keep their heels flat on the ground or board. Any movement that is plyometric in nature (such as running and jumping as is required in the game of cricket) is performed from the forefoot. The muscle chain that is activated when initiating movement from the heel of the foot (anterior muscle chain), differs from the muscle chain that is activated when performing a movement from the front of the foot (posterior muscle chain).[155] It is therefore doubtful that the biomechanics of the FMS DS simulate the biomechanics of the basic athletic movement patterns where cricketers could get injured. For this reason, even if an adapted movement pattern is recognised during the performance of the FMS DS, the interpretation of the score might not be relevant to the athlete's risk of sustaining an injury. Considering the above one might question if the FMS is an actual measure of compensatory movement patterns or merely a description of ways different individuals execute certain movement patterns.

The principle of dynamic correspondence,[150] which was introduced in the previous section, is also relevant to the construct validity of the FMS movement patterns. This principle as well as findings by Frost et al. 2013[156] suggest that because a muscle or muscle chain is effective or a skill is mastered at one velocity or load does not mean it will translate to the correct technique or activation in a different pattern, at a different velocity or under a different load.[150] In fact, Frost et al., 2013[156] found significant differences in the manner of execution of basic movements (deadlift, squat, lunge and push) at different velocities and at different loads. The developers of the FMS do not describe any specific speed at which the movements should be executed and all movements are therefore done at the participants' self-selected speed (velocity). Furthermore, except for body weight, the movements are done without any additional load. If this is not the velocity or load required by the athlete's sport or individual's activity then the test lacks construct validity.[154]

As shown in the literature review (Chapter 2) and the discussion of Chapter 5, inconsistencies in construct validity of the total cut-off score also exist. As the FMS total score is a sum of multiple tests, construct validity would not only relate to that of each test but also the sum of the results of the individual tests.[152] In order to use the FMS total score, internal consistency between the individual test scores should be established. Simply put, it should first be established how closely the individual movement patterns are related to each other. Using Chronbach's α, three studies[122],[123],[118] have found poor internal consistency (α=0.39-0.58) between the seven FMS subtests. Kraus et al. (2014)[152] further noted that the FMS does not appear to be a unitary construct and a cut-off score should not be used as such. These findings suggest that the individual movement patterns should rather be treated as individual tests in themselves as opposed to a combined screening procedure. However, considering the findings related to the construct validity of the movement patterns as discussed above, further research is warranted before implementation in a sport medicine settings.

Criterion-reference validity of manual grading of the FMS

Similar to the design of Paper 3, Whiteside et al. (2014)[157] compared certified FMS rater scores to joint angle measurements recorded on an objective inertial-based motion capture system. Authors of this paper also based specific pre-determined joint

angle thresholds on FMS scoring criteria. This study[157] found that the criterion-reference validity of the FMS was limited and suggested that more explicit grading guidelines need to be set.

Concurrent validity: Previous injury

The basic premise on which the FMS was designed was that injury causes changes in structure and motor control which can lead to inefficient, compensatory movement patterns.[19] Several studies therefore hypothesised that compared to participants with no history of previous injury, participants with a history of injury or surgery would score lower on the FMS test. Schneiders et al. (2011)[117] and Agresta et al. (2014)[124] found no difference in total FMS score between participants who were currently injury free but had sustained an injury in the previous six or twelve months respectively and those who did not. Chimera et al. (2014)[92] found an association between injuries to specific joints and individual FMS tests, but no association between total FMS score and previous injury. It would therefore seem that the most basic premise on which the FMS was based is not supported by research.

8.3.3 The use of FMS screening in conjunction with other screening procedures in the prediction of injuries

The findings of Paper 2 (Chapter 5) as well as numerous other studies have shown that the FMS in isolation is not a valid predictor of injury. Lehr et al. (2014)[146] designed the Move2Perform algorithm comprising the results of a series of tests in an attempt to quantify injury risk among a group of athletes. The series of tests comprised of the Y-Balance test (composite risk cut score and asymmetry), previous history (demographic and injury history) and the FMS (total score, asymmetries and pain with testing). These test results, with various evidence based weightings and interactions, were entered into the algorithm to categorise athletes as high or low risk of injury. The study concluded that the combination of these efficient, low-cost, field-ready tests can help identify individuals with increased risk of noncontact lower limb injuries.[146]

8.3.4 The use of FMS in the prediction of contact injuries

Like the developers of the FMS, the writer of this dissertation hypothesised that more

efficient execution of functional movement patterns could result in better athletic performance. In turn, better athletic performance could allow an athlete to avoid contact resulting in injury. For this reason, several rugby, football and American football (all contact sports) teams still include the FMS in their screening regimes.[158] Burger et al. (2014)[159] have for example shown that poor tackling technique increases injury risk among junior SA rugby players. Tee (2015)[158] subsequently linked poor tackling technique to a low FMS DS score (See Figure 8.1) by hypothesising that dysfunction in this movement pattern may make it difficult for players to get into an ideal tackling position. When playing on offence, these dysfunctional patterns might not allow a player to avoid an avoidable contact situation.

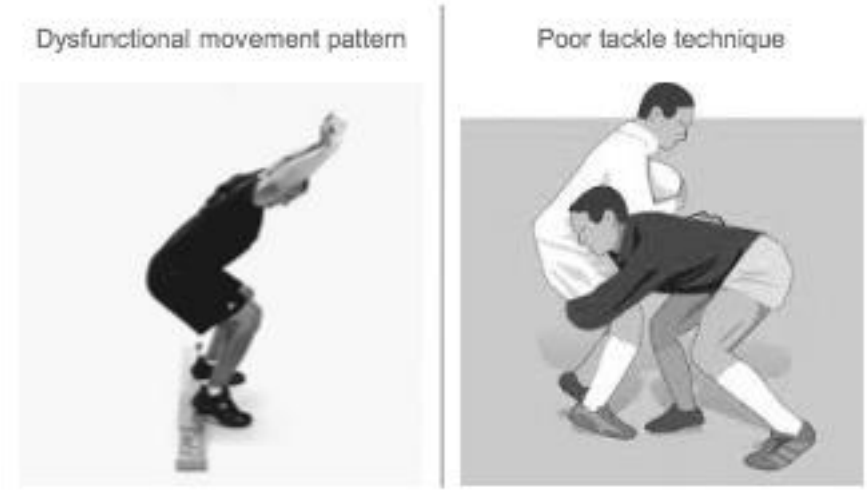


Figure 8-1: Relationship of DS movement dysfunction and poor tackling technique in rugby[158]

However, subsequent research has shown that the FMS is not a direct athletic performance metric.[154] Studies investigating differences in FMS scores among athletes at various levels did not support this hypothesis.[160,161] Moreover, when performance of athletes on different athletic tests that score differently to the FMS were compared, no association was found.[100,56,162,127]

Contrary to the conflicting findings regarding the use of the FMS total score to address predict injury, there seems to be consensus that the FMS is not a valid measure for predicting athletic performance.[128]

CHAPTER 9

9 CONCLUSION

The inherent nature of the pace bowling action, combined with intrinsic risk factors related to the adolescent growth spurt, predispose high school pace bowlers to injury. This is confirmed by the high prevalence of injuries in adolescent pace bowlers.

When designing or incorporating a screening procedure into injury prevention strategies, all possible mechanisms (contact and non-contact) of injury the athlete might be exposed to should be taken into consideration. Risk factors related to functional movement patterns and abdominal muscle morphometry were previously only associated with non-contact injuries. The results of Papers 1 (lateral abdominal muscle morphometry and injury) and paper 2 (FMS and injury) show that these intrinsic risk factors might also be associated with contact injuries and not only non-contact injuries.

The results of Paper 1 and Paper 3 respectively place doubt on the predictive validity of the total FMS score and concurrent validity of the FMS DS. Furthermore the FMS movement patterns which have low level demands (i.e. movements that are performed at slower velocity and lower load than actual sporting activity), may not reflect an individual's normal compensatory patterns or risk of injury and could therefore affect training and rehabilitation recommendations. The current FMS test movements does not seem relevant to evaluate risk of injury during the performance of cricket related activities. Before the FMS is included as part of screening procedures in other sporting disciplines the biomechanics of the movement patterns of that specific sport should be compared to those of the FMS sub-tests.

9.1 STRENGTH OF THE STUDY

By applying strict inclusion and exclusion criteria (bowlers that were injury free, playing at the same level (high school) and were within a narrow age range (13 to 18 years)) a homogeneous group of participants were investigated in all papers in this dissertation.

Injury surveillance in Papers 1 and 2 was longitudinal in nature which differs from most previous research that are largely cross-sectional investigations. Longitudinal assessments are less susceptible to variables that can change from one day to the next and are therefore less prone to deceptive conclusions. 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 and 2) 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 ultrasound measurements in Paper 2 as well as the kinematic analysis system in Papers 3 are considered as strengths of these papers. Scientific conclusions that are based on measures made by objective outcome measures can be converted into sound, clinical recommendations.

Despite the above detailed strengths of the studies, a number of limitations, which are described in the section hereafter, must be acknowledged in the interest of improved study design of subsequent research.

9.2 LIMITATIONS

Although studies in this dissertation have sample sizes comparable to studies of a similar nature, the small sample size of the contact/ non-contact sub-groups in papers 1 and 2 makes the results susceptible to a type II error.

Another limitation related to kinematic movement analysis is the occurrence of skin movement artefact. Light reflective markers are used on the surface of the skin and movement of the skin cannot be controlled for. This may increase the error in the data. This limitation can be overcome to some extent by the use of bone pins; however, this is an invasive method and introduces many ethical dilemmas.

Only adolescent, school boy level, pace bowlers were included in the studies and although this contributes to the homogeneity of the population group, it also limits the generalisability of the results.

For the purposes of paper 2 only one observer scored the participants performance of the FMS movements. Although the observer was experienced in the use of the FMS in clinical practice, a standard set of scoring criteria was used and the observer was blinded to participants' previous injuries, the scoring is still susceptible to confirmation bias.

During the observed study period, the researcher did not have control over participants' participation in sports other than cricket. Participation in additional sporting activities would inevitably affect workload which might have impacted the results.

9.3 RECOMMENDATIONS

9.3.1 Future research recommendations

The majority of studies investigating abdominal muscle morphometry of cricket pace bowlers have always done so with the participants in a supine position. Even though similar participant positions and procedures were followed, these studies had conflicting results. Future research should investigate morphometry and morphology of

these muscles in an upright bipedal or unipedal position, which is more representative of the positions assumed when playing cricket and other unilateral rotational sports.

Developers of the FMS have set out the rationale and clinical implications for including each individual test included in the FMS. However, studies investigating the validity of the FMS have had conflicting results. Future research could therefore investigate if the biomechanics of the movements included in the FMS are in fact truly representative of the biomechanics of basic athletic skills such as running, jumping and throwing in which injuries might occur. The quest in finding the ultimate screening tool which has a high predictive validity is still on.

The impact of simultaneous participation in multiple sports, especially those unilateral in nature, on the workload and resultant effect on the abdominal muscle morphology and functional movement patterns of the adolescent pace bowlers should also be investigated.

9.3.2 Clinical recommendations

The physical, emotional, social and psychological benefits of participation in sport among adolescents have been well documented.[34] Injury during adolescence can cause long term disability for the adolescent athlete. Therefore, incorporating preventive strategies aimed at identifying and reducing injury risk may facilitate the development of young injury free pace bowlers which may in turn, have an impact on the athlete's career as well as health care costs.

The particular screening tool or programme incorporated should not, however, be based on novelty or popularity, but rather on sound scientific proof of the effectiveness thereof. Furthermore, the quality of the preventative strategies should not be compromised for the sake of user-friendliness or saving time or short-term cost.

Although amateur and school sports teams might not be able to acquire USI equipment due to financial constraints, this screening method is simple and user-friendly. While the findings of Paper 1 and other published research suggest some association between lateral abdominal muscle morphometry, morphology and injury, many conflicting conclusions exist with regards to the exact role of the different muscles forming the lateral abdominal wall in the prevention of injury. Cost should

therefore be weighed up against benefit before implementing this method as part of a screening regimen.

While the FMS is user-friendly and both time and cost effective, evidence for using the FMS in isolation to predict injury among various groups of athletes is conflicting. More specifically, research regarding the association of FMS scores and injury among cricket pace bowlers are scarce and the findings of Paper 2 does not advocate for the use of the FMS as a pre-season screening tool for this group of athletes. Based on the results of this study, health and strength conditioning professionals might consider the use of the FMS together with other validated screening procedures in an attempt to identify individuals with high risk of injury, but should not use the FMS as an isolated screening tool.

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APPENDIX A: Functional Movement Screen Information Sheet

Functional Movement Screen (Cook, 2001)

TEST 1 DEEP SQUAT

Purpose - The DS is used to assess bilateral, symmetrical, mobility of the hips, knees, and ankles. The dowel held overhead assesses bilateral, symmetrical mobility of the shoulders as well as the thoracic spine.

Description - The individual assumes the starting position by placing his/her shoulder width apart. The individual then adjusts their hands on the dowel to assume a 90-degree angle of the elbows with the dowel overhead. Next, the dowel is pressed overhead with the shoulders flexed and abducted, and the elbows extended. The athlete is then instructed to descend slowly into a squat position. As many as 3 repetitions should be performed. The squat position should be assumed with the heels on the floor, head and chest facing forward, and the dowel maximally pressed overhead.

3 Points

Upper torso is parallel with tibia or toward vertical
Femur is below horizontal
Knees are aligned over feet
Dowel is aligned over feet



2 Points
Upper torso is parallel with tibia or toward vertical
Femur is below horizontal
Knees are not aligned over feet
Dowel is aligned over feet



1 Point
Upper torso is not parallel with tibia
Femur is not below horizontal
Knees are not aligned over feet
Lumbar flexion is noted



0 Points
Pain is associated with any part of the test.
Sports Medicine follow up.

Clinical Implications for DS
The ability to perform the DS requires closed-kinetic chain dorsi-flexion of the ankles, flexion of the knees and hips, extension of the thoracic spine, as well as flexion and abduction of the shoulders.
Poor performance of this test can be the result of several factors. Limited mobility in the upper torso can be attributed to poor gleno-humeral and/or thoracic spine mobility. Limited mobility in the lower extremity including poor closed-kinetic chain dorsi-flexion of the ankle and/or poor flexion of the hip may also cause poor test performance.
When an athlete achieves a score less than **3**, the limiting factor must be identified.

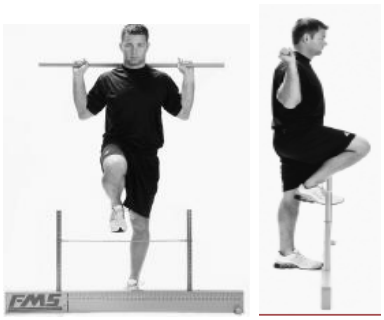
TEST 2 HURDLE STEP

Purpose - The Hurdle Step is used to assess bilateral mobility and stability of the hips, knees, and ankles.

Description - The individual assumes the starting position by placing his/her feet shoulder width apart. The hurdle is then adjusted to the height of the athlete's tibial tuberosity. The dowel is positioned across the athlete's shoulders below their neck. The individual then aligns their toes directly beneath the hurdle. The athlete is then asked to step over the hurdle and touch the heel while maintaining his/her stance leg in an extended position. Finally, the athlete is instructed to return to the starting position. The Hurdle Step should be performed slowly and as many as 3 times bilaterally. If one repetition is completed bilaterally meeting the below criteria a 3 is given.

3 Points

Hips, knees and ankles remain aligned in the sagittal plane.
Minimal to no movement noted in lumbar spine.
Dowel and hurdle remain parallel.



2 Points
Hip, knee and ankle alignment lost.
Movement noted in lumbar spine.
Dowel and hurdle do not remain parallel.



1 Point
Contact between foot and hurdle occurs.
Loss of balance is noted.



0 Points
Pain is associated with any part of the test.

Clinical Implications for Hurdle Step

The ability to perform the Hurdle Step test requires both stance leg stability of the ankle, knee, and hip as well as maximal closed-kinetic chain extension of the hip. The Hurdle Step also requires leg open-kinetic chain dorsi-flexion of the ankle and flexion of the knee and hip. The athlete must also display adequate single leg stance balance during this test.
Poor performance of this test can be the result of several factors. It may simply be due to poor stability of the stance leg or poor mobility of the step leg. However, imposing maximal hip flexion of one leg while maintaining apparent hip extension of the opposite leg requires the athlete to demonstrate relative,
Asymmetric hip mobility.

TEST 3 IN-LINE LUNGE

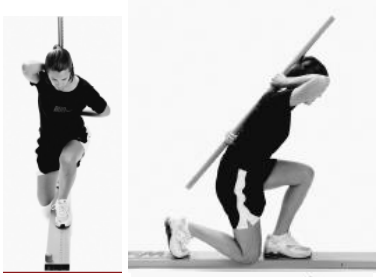
Purpose - The In-Line Lunge is used to assess bilateral mobility and stability, as well as ankle and knee stability.

Description - The tester measures the individual's tibial length with a tape measure. The athlete then places one foot on the end of the 2" x 6" board. The athlete places the dowel behind their back touching the head, thoracic spine, and sacrum. The hand ipsi-lateral to the back foot should be the hand grasping the top of the dowel; the contra-lateral hand grasps the bottom. The tester then measures the tibial length from the end of the individual's toes and a mark is made on the board. The athlete is then asked to take a step and place their heel on the mark. The athlete then lowers their back knee enough to touch the board behind the front foot. The feet should be on the same line and pointing straight throughout the movement. The lunge is performed up to three times bilaterally in a slow controlled fashion. If one repetition is completed successfully then a three is given.

3 Points
Minimal to no torso movement is noted.
Feet remain parallel in sagittal plane on board.
Knee touches board behind heel of front foot.



2 Points
Torso movement is noted.
Feet do not remain parallel in sagittal plane.
Knee does not touch board behind heel of front foot.



1 Point
Loss of balance is noted.



0 Points
Pain is associated with any part of the test.

Clinical Implications for In-Line Lunge

The ability to perform the In-Line Lunge test requires stance leg stability of the ankle, knee, and hip as well as closed-kinetic chain hip abduction. The In-Line Lunge also requires step leg mobility of the hip adduction and ankle dorsi-flexion. The athlete must also display adequate balance during this test.
Poor performance of this test can be the result of several factors. First of which is inadequate hip mobility of either the stance or step leg. Secondly, the stance leg knee or ankle may not have the required stability as the lunge is performed. Thirdly, an imbalance may be present between adductor weakness and abductor tightness about one or more hips. Finally, tightness of the rectus femoris on the stance leg may lead to impaired performance.

TEST 4 SHOULDER MOBILITY

Purpose - The Shoulder Mobility test is used to assess bilateral shoulder range of motion combining internal rotation with adduction and external rotation with abduction.

Description - The tester first determines the athlete's hand length by measuring the distance from the distal wrist crease to the tip of the third digit. The athlete is instructed to make a fist with each hand, placing the thumb inside the fist. They are then asked to assume a maximally adducted and internally rotated position with one shoulder, and a maximally abducted and externally rotated position with the other. During the test the hands should remain in a fist and they should be placed on the back in one smooth motion. The tester then measures the distance between the two fists. Perform the Shoulder Mobility test as many as 3 times bilaterally.

3 Points
Fists are within one hand length.



2 Points
Fists are within one and a half hand lengths.



1 Point
Fists are not within one and a half hand lengths.



** A shoulder stability screen should be performed even if the athlete scores a **3**. The athlete places his/her hand on the opposite shoulder and then attempts to point the elbow upward. If there is pain associated with this movement, a score of **0** is given. It is recommended that a thorough evaluation of the shoulder be done. This screen should be performed bilaterally. If the athlete does receive a score of **0** both scores should be documented for future reference.*

Clinical Implications for Shoulder Mobility

The ability to perform the Shoulder Mobility test requires shoulder mobility in a combination of motions including abduction/external rotation and adduction/internal rotation.
Poor performance of this test can be the result of several factors. One of which is the widely accepted factor that increased external rotation is gained at the expense of internal rotation in overhead throwing athletes. There can also be postural changes of forward or rounded shoulders caused by excessive development and shortening of the pectoralis minor and/or Latissimus dorsi muscles. Finally a scapula-thoracic dysfunction may be present resulting in decreased gleno-humeral mobility.

TEST 5 ACTIVE STRAIGHT LEG RAISE

Purpose - The Active Straight Leg Raise test is used to assess active hamstring and gastrocnemius/soleus flexibility, while maintaining a stable pelvis.

Description - The individual first assumes the starting position by lying supine with his/her arms at their sides, palms up and head flat on the floor. The 2" x 6" is placed under the knees of the athlete. The tester then identifies the athlete's anterior superior iliac spine (ASIS) and mid-point of the patella. Next, the athlete is instructed to lift the test leg with a dorsi-flexed ankle and an extended knee. During the test the opposite knee should remain in contact with the 2" x 6" and head should remain flat on the floor. Once the athlete has achieved their end range position, a dowel is aligned along the medial malleolus of the test leg, perpendicular to the floor. The Active Straight Leg Raise test should be performed as many as 3 times bilaterally.

3 Points
Dowel resides between mid-thigh and ASIS.



2 Points
Dowel resides between mid-thigh and the joint line.



1 Point
Dowel resides below the joint line.



0 Points
Pain is associated with any part of the test.

Clinical Implications for Active Straight Leg Raise

The ability to perform the Active Straight Leg Raise test requires functional hamstring flexibility. This flexibility is the true flexibility an athlete has available during training and competition, as opposed to passive flexibility, which is most often assessed. The athlete is also required to demonstrate adequate passive iliopsoas flexibility of the opposite leg as well as lower abdominal stability.
Poor performance during this test can be the result of several factors. First, the athlete may have poor functional hamstring flexibility. Secondly, inadequate passive mobility of the opposite hip may be the result of iliopsoas tightness associated with an anterior tilted pelvis. If this limitation is gross, true active hamstring flexibility will not be realized. A combination of both these factors will demonstrate an athlete's relative bilateral, asymmetric hip mobility. This is similar to the relative hip mobility revealed by the Hurdle Step, however, this test is more specific to the limitations imposed by the muscles of the hamstrings and the iliopsoas.

TEST 6 TRUNK STABILITY PUSH-UP

Purpose - The Trunk Stability Push-Up is used to assess trunk stability in the sagittal plane while a symmetrical upper extremity motion is performed.

Description - The individual assumes a prone position. The hands are then placed shoulder width apart at the appropriate position per the below criteria, knees fully extended. The individual is asked to perform one push-up in this position. The body should be lifted as a unit; there should be no "lag" in the lumbar spine when performing this push-up. If the individual cannot perform a push-up in this position, the hands are lowered to the appropriate position per the below criteria, and a push-up is performed. The Trunk Stability Push-Up can be performed as many as 3 times.

3 Points
Males perform one repetition with thumbs aligned with top of head.
Females perform one repetition with thumbs aligned with the chin.



2 Points
Males perform one repetition with thumbs aligned with top of head.
Females perform one repetition with thumbs aligned with the chin.





1 Point
Males are unable to perform one repetition in modified position.
Females are unable to perform one repetition in modified position.



*Lumbar extension should also be cleared after this test, even if a score of **3** is given. Spinal extension can be cleared by performing a press-up in the push-up position. If there is pain associated with this motion, a **0** is given and a more thorough evaluation should be performed*

Clinical Implications for Trunk Stability Push-Up
The ability to perform the Trunk Stability Push-up requires symmetric trunk stability in the sagittal plane during a symmetric upper extremity movement. Many functional activities in sport require the trunk stabilizers to transfer force symmetrically from the upper extremities to the lower extremities and vice versa. Movements such as rebounding in basketball, overhead blocking in volleyball, or pass blocking in football are common examples of this type of energy transfer. If the trunk does not have adequate stability during these activities, kinetic energy will be dispersed, leading to poor functional performance as well as increased potential for micro-traumatic injury.
Poor performance during this test can be simply attributed to poor symmetric stability of the trunk stabilizers.

TEST 7 ROTATIONAL STABILITY

Purpose - The Rotational Stability test is used to assess multi-planar stability while a combined upper and lower extremity motion is performed.

Description - The individual assumes the starting position in quadruped with their shoulders and hips at 90 degrees relative to the upper torso. The knees are positioned at 90 degrees and the ankles should remain dorsi-flexed. The 2" x 6" is the placed between the knees and hands so they are in contact with the board. The individual then flexes the shoulder and extends the same side hip and knee. The leg and hand are only raised enough to clear the floor by approximately 6 inches. The elbow, hand, and knee that are lifted should all remain in line with the 2" x 6". The torso should also remain in the same plane as the 2" x 6". The same shoulder and knee are then flexed enough for the elbow and knee to touch. This is performed bilaterally for up to 3 repetitions.

3 Points

Athlete performs one correct repetition while keeping torso parallel to the board and elbow and knee in line with the board.





2 Points

Athlete performs one correct diagonal flexion and extension lift while keeping torso parallel to board and floor.





1 Point

Athlete unable to perform diagonal repetition.





*Lumbar flexion should also be cleared after this test, even if a score of **3** is given. Spinal flexion can be cleared by assuming a quadruped position, rocking back and taking the buttocks to the heels and the chest to the thighs. The hands should remain in front of the body, reaching out as far as possible; feet and toes should be plantar flexed. If there is pain associated with this motion, a **0** is given and a more thorough evaluation should be performed.*

Clinical Implications For Rotational Stability

The ability to perform the Rotational Stability test requires asymmetric trunk stability in both sagittal and transverse planes during asymmetric upper and lower extremity movement. Many functional activities in extremities and vice versa. Running and accelerating out of a down stance in track and football are common examples of this type of energy transfer. If the trunk does not have adequate stability during these activities, kinetic energy will be dispersed, leading to poor performance as well as increased potential for micro traumatic injury. Poor performance during this test can be simply attributed to poor asymmetric stability sport require the trunk stabilizers to transfer force asymmetrically from the lower extremities to the upper

APPENDIX B: FMS Score Sheet

SUBJECT NR.		DATE:	
TYPE OF PACE BOWLER:		MEDIUM/FAST	
HAND DOMINANCE:		RIGHT / LEFT	
LEG DOMINANCE:		RIGHT / LEFT	
HEIGHT (CM):			
WEIGHT (KG):			

	TEST		RAW SCORE	FINAL SCORE	COMMENTS
1	DEEP SQUAT				
2	HURDLE STEP	L			
		R			
3	IN-LINE LUNGE	L			
		R			
4	SHOULDER MOBILITY	L			
		R			
4A	IMPINGEMENT CLEARING TEST	L			
		R			
5	ACTIVE STRAIGHT LEG RAISE	L			
		R			
6	TRUNK STBILITY PUSH-UP	L			
		R			
6A	PRESS-UP CLEARING TEST				
7	ROTATORY STABILITY	L			
		R			
7A	POSTERIOR ROCKING CLEARING TEST				
	TOTAL				

Raw Score: This score is used to denote right and left side scoring. The right and left sides are scored in five of the seven tests and both are documented in this space.
Final Score: This score is used to denote the overall score for the test. The lowest score for the raw score (each side) is carried over to give a final score for the test. A person who scores a three on the right and a two on the left would receive a final score of two. The final score is then summarized and used as a total score.

APPENDIX C:USI Measured Lateral Abdominal Muscles

SUBJECT NR. **DATE:**

WHILE AT REST	**LEFT (mm)**	**RIGHT (mm)**
Transverse Abdominis		
Internal Oblique		
External Oblique		
WHILE PERFORMING ADIM	**LEFT (mm)**	**RIGHT(mm)**
Transverse Abdominis		
Internal Oblique		
External Oblique		

APPENDIX D: 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 computor 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 ☐ Weigth 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:_____

APPENDIX E: Monthly 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			
2013 off season			
2012			
2011			
2010-2009			
2008-2007			
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:			

APPENDIX F: 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 ☐ Weigth 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 prevened?

☐ 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:_____

Thank you very much for participation in this research project!

APPENDIX G: Ethical Clearance Certificate

M130657

R14/49 Candice Martin

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M130657

NAME: (Principal Investigator)	Candice Martin
DEPARTMENT:	Physiotherapy Marica Kok Physiotherapist t/a Menlo-Physio
PROJECT TITLE:	Prediction of Injury in High School Cricket Pace Bowlers
DATE CONSIDERED:	28/06/2013
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	Benita Olivier
APPROVED BY:	Professor PE Cleaton-Jones, Chairperson, HREC (Medical)

DATE OF APPROVAL: 22/07/2013

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Secretary in Room 10004, 10th floor, Senate House, University.

I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report**.

Principal Investigator Signature Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

APPENDIX H: Gauteng Department of Education (GDE) Approval Letter

GAUTENG PROVINCE
Department: Education
REPUBLIC OF SOUTH AFRICA

For administrative use:
Reference no. D2014/094

GDE RESEARCH APPROVAL LETTER

Date:	**18 July 2013**
Validity of Research Approval:	**18 July 2013 to 20 September 2013**
Name of Researcher:	**Martin C.**
Address of Researcher:	**168 Lorinda Street**
	Murrayfield
	0184
Telephone Number:	**012 348 6265 / 083 254 2595**
Fax Number:	**012 348 6466**
Email address:	**candice.mailme@gmail.com**
Research Topic:	**The functional movement screen and abdominal muscle activation in the prediction of injuries in High school cricket pace bowlers**
Number and type of schools:	**FIVE Secondary Schools**
District/s/HO	**Tshwane South**

Re: Approval in Respect of Request to Conduct Research

This letter serves to indicate that approval is hereby granted to the above-mentioned researcher to proceed with research in respect of the study indicated above. The onus rests with the researcher to negotiate appropriate and relevant time schedules with the school/s and/or offices involved to conduct the research. A separate copy of this letter must be presented to both the School (both Principal and SGB) and the District/Head Office Senior Manager confirming that permission has been granted for the research to be conducted.

The following conditions apply to GDE research. The researcher may proceed with the above study subject to the conditions listed below being met. Approval may be withdrawn should any of the conditions listed below be flouted:

2013/07/19

Office of the Director: Knowledge Management and Research
9th Floor, 111 Commissioner Street, Johannesburg, 2001
P.O. Box 7710, Johannesburg, 2000 Tel: (011) 355 0506
Email: David.Makhado@gauteng.gov.za
Website: www.education.gpg.gov.za

APPENDIX I: Information Leaflet - Principals of Schools

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

Dear Sir/Madam

My name is Candice Martin. I am currently enrolled for a Master's degree in Physiotherapy at the University of the Witwatersrand. I am doing research to determine if the Functional Movement Screen (FMS) and the thickness of various abdominal muscles are predictors of injury among pace bowlers. I will be most grateful if you are willing to let selected bowlers from the various cricket teams participate in this study.

Why is this study important?

If it can be established that both the FMS and Abdominal wall muscle thickness are predictors of injury, these tools can be used pre-season to determine which bowlers are at risk of sustaining in-season injuries. In addition, these screening tools can help identify any functional movement limitations and asymmetries a bowler might have. This is important because these physical factors are related to injury and may be related to performance as well. Fitness professionals and bowlers can then take the pre-cautionary steps to prevent injuries before they occur.

What would the pace bowler be expected to do?

The bowlers will be asked to complete and take part in a series of tests. None of these tests are invasive and will not inflict any pain or discomfort. Tests include performance of seven FMS tests as well as measurement of the abdominal muscle wall using Ultrasound. FMS tests include: deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk-stability push-up and rotational stability test as well as three clearing tests, shoulder impingement test, lumbar extension and flexion test. An observer will observe and score the various movements. Video analysis of these tests will also be done. All of these tests will be done at the start of the season. They will be required to wear, short dark ski-pants and white t-shirt. The FMS tests will be done barefoot. This is necessary so that reflective markers can be attached in order to get an accurate view of joint movement. These

measurements will take place during one of your training sessions and will take approximately one hour.

During the season (3 months) they will be required to report details surrounding injuries sustained. I will contact the coaches each month and if an injury was sustained during that month, the bowler will be required to complete a questionnaire on the mechanism of injury and matches missed.

Participation is completely voluntary and they may withdraw at any time. The bowlers will not suffer any consequences and do not have to provide a reason should you decide not to participate.

What are the benefits to the participants?

Injury prevention guidelines will be developed based on the results of this study. These injury prevention guidelines will be given to each bowler and his coach. In addition, the report and video analysis of the FMS and abdominal muscle thickness will be given to the coaches and conditioning specialist. This will enable them to identify and correct the bowlers' limitations and asymmetries.

Will information be handled as confidential?

Names of participants will only be written on the consent form and not on the questionnaire. Consent forms will be kept separately from the questionnaires. All information will be confidential and will only be used for the purpose intended for this study. All bowlers will be assigned a study number. The key to the study numbers assigned will be kept in the possession of the researcher only.

For more information, or if you have any queries, please phone me at 083 254 2595.

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

Yours truly



CANDICE MARTIN (PHYSIOTHERAPIST)

APPENDIX J: Informed Consent Principals of Schools

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

I_____ hereby agree to let my school's pace bowlers participate in this study as described to me in the information sheet. By signing this form I am agreeing for them to complete the questionnaires, participate in the Functional Movement Screen and ultrasound measurement of abdominal musculature as well as video analysis.

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

Signature _____ Witness _____

Date _____

APPENDIX K: Information Leaflet - Bowlers

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

Dear Pace Bowler

My name is Candice Martin. I am currently enrolled for a Masters degree in physiotherapy at the University of the Witwatersrand. I am doing research to determine if the Functional Movement Screen (FMS) and the thickness of various abdominal muscles are predictors of injury among pace bowlers. I will be most grateful if you would be willing to participate in this research.

Why is this study important?

If it can be established that both the FMS and Abdominal wall muscle thickness are predictors of injury, these tools can be used pre-season to determine which bowlers are at risk of sustaining in-season injuries. In addition, these screening tools can help identify any functional movement limitations and asymmetries a bowler might have. This is important because these physical factors are related to injury and may be related to performance as well. Fitness professionals and bowlers can then take the pre-cautionary steps to prevent injuries before they occur.

What would you be expected to do?

You will be asked to complete and take part in a series of tests. None of these tests are invasive and will not inflict any pain or discomfort. Tests include performance of seven FMS tests as well as measurement of the abdominal muscle wall using Ultrasound. FMS tests include: deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk-stability push-up and rotational stability test as well as three clearing tests, shoulder impingement test, lumbar extension and flexion test). An observer will observe and score the various movements. Video analysis of these tests will also be done. All of these tests will be done at the start of the season. You will be required to wear, short dark ski-pants and white t-shirt. The FMS tests will be done bare foot. This is necessary so that reflective markers can be attached in order to get an accurate view of joint movement. These measurements will take place during one of your training sessions and will take approximately one hour. During the season (4 months) you will be required to report details surrounding injuries

sustained. I will contact you each month and if an injury was sustained during that month, you will be required to complete a questionnaire on the mechanism of injury and matches missed. Participation is completely voluntary and you may withdraw at any time. You will not suffer any consequences, and you do not have to provide a reason should you decide not to participate.

What are the benefits to the participants?

Injury prevention guidelines will be developed based on the results of this study. These injury prevention guidelines will be given to each bowler and his coach. In addition, the report and video analysis of your FMS and abdominal muscle thickness will be given to your coach and conditioning specialist. This will enable you to identify and correct your limitations and asymmetries.

Will information be handled as confidential?

Names of participants will only be written on the consent form and not on the questionnaire. Consent forms will be kept separately from the questionnaires. All information will be confidential and will only be used for the purpose intended for this study. All bowlers will be assigned a study number. The key to the study numbers assigned will be kept in the possession of the researcher only.

For more information, or if you have any queries, please phone me at **083 254 2595.**

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

Yours truly



CANDICE MARTIN (PHYSIOTHERAPIST)

APPENDIX L: Information leaflet parents of Bowlers Younger than 18

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

Dear Sir/Ma'am

My name is Candice Martin. I am currently enrolled for a Masters degree in physiotherapy at the University of the Witwatersrand. I am doing research to determine if the Functional Movement Screen (FMS) and the thickness of various abdominal muscles are predictors of injury among pace bowlers. I will be most grateful if you would be willing to participate in this research.

Why is this study important?

If it can be established that both the FMS and Abdominal wall muscle thickness are predictors of injury, these tools can be used pre-season to determine which bowlers are at risk of sustaining in-season injuries. In addition, these screening tools can help identify any functional movement limitations and asymmetries a bowler might have. This is important because these physical factors are related to injury and may be related to performance as well. Sports conditioning professionals and bowlers can then take the pre-cautionary steps to prevent injuries before they occur.

What would the bowlers be expected to do?

The bowlers will be asked to complete and take part in a series of tests. None of these tests are invasive and will not inflict any pain or discomfort. Tests include performance of seven FMS tests as well as measurement of the abdominal muscle wall using Ultrasound. FMS tests include: deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk-stability push-up and rotational stability test as well as three clearing tests, shoulder impingement test, lumbar extension and flexion test). An observer will observe and score the various movements. Video analysis of these tests will also be done. All of these tests will be done at the start of the season. They will be required to wear, short dark ski-pants and white t-shirt. The FMS tests will be done barefoot. This is necessary so that reflective markers can be attached in order to get an accurate view of joint movement. These

measurements will take place during one of your training sessions and will take approximately one hour. During the season (4 months) they will be required to report details surrounding injuries sustained. I will contact them each month and if an injury was sustained during that month, they will be required to complete a questionnaire on the mechanism of injury and matches missed. Participation is completely voluntary and they may withdraw at any time. They will not suffer any consequences and do not have to provide a reason should you decide not to participate.

What are the benefits to the participants?

Injury prevention guidelines will be developed based on the results of this study. These injury prevention guidelines will be given to each bowler and his coach. In addition, the report and video analysis of their FMS and abdominal muscle thickness will be given to the coaches and conditioning specialist. This will enable them to identify and correct these limitations and asymmetries.

Will information be handled as confidential?

Names of participants will only be written on the consent form and not on the questionnaire. Consent forms will be kept separately from the questionnaires. All information will be confidential and will only be used for the purpose intended for this study. All bowlers will be assigned a study number. The key to the study numbers assigned will be kept in the possession of the researcher only.

For more information, or if you have any queries, please phone me at **083 254 2595.**

If you are willing to let your child participate in this study, please fill in and sign the consent form attached.

Yours truly



CANDICE MARTIN (PHYSIOTHERAPIST)

APPENDIX M: Informed Consent - Parents of Bowlers

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

I_____ hereby give consent that _____ may participate in the study as described in the information sheet. By signing this form I am agreeing that he will fill in the questionnaire, participate in the Functional Movement Screen and ultra-sound measurement of my abdominal musculature.

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

Signature _____

Witness _____

Date _____

APPENDIX N: Informed Consent/Assent – Bowlers

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

I_____ hereby agree to participate in the study as described to me in the information sheet. By signing this form I am agreeing to filling in the questionnaire, participate in the Functional Movement Screen and ultra-sound measurement of my abdominal musculature.

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 O: Informed Consent for Video Capturing - Parents of Bowlers Younger than 18

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

I_____ hereby give consent that _____ may participate in the study as described in the information sheet. By signing this form I am agreeing that he can participate in the video capturing and the analysis of me performing the Functional Movement Screen.

Signature _____ Witness _____

Date _____ Date _____

APPENDIX P: Informed Consent/Assent for Video Capturing - Bowlers

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Tel: (012) 348 6265 • Fax: 012 348 6466 • e-mail: candice.mailme@gmail.com

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 me performing the Functional Movement Screen.

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 _____ Date _____

APPENDIX Q: Turnitin report

Candice Martin Dissertation Draft 9

ORIGINALITY REPORT

%15	%12	%10	%2
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.ncbi.nlm.nih.gov Internet Source	%1
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