INVESTIGATION INTO LUMBAR SPINE INJURY RISK FACTORS DURING FAST BOWLING IN JUNIOR CRICKETERS

A thesis submitted to Charles Sturt University in the fulfilment of the requirements for the degree

Doctor of Philosophy

by

Andrew Schaefer

Bachelor of Exercise Science (Rehabilitation)
Bachelor of Exercise Science (Honours)

August 2017
School of Exercise Science, Sport and Health
Faculty of Science
Charles Sturt University
Bathurst NSW 2795
Australia
Dedication

This thesis is dedicated to those who have played some part in aiding me complete this thesis and I am truly grateful.
Declaration

I, Andrew Schaefer, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at Charles Sturt University or any other educational institution, except where due acknowledgement is made in the thesis “Investigation into lumbar spine injury risk factors during fast bowling in junior cricketers”. Any contribution made to the research by colleagues with whom I have worked at Charles Sturt University or elsewhere during my candidature is fully acknowledged. I agree that this thesis be accessible for the purpose of study and research in accordance with the normal conditions established by the Executive Director, Library Services or nominee, for the care, loan and reproduction of theses.

Andrew Schaefer

27/06/18
Publications & Presentations

Conference Proceedings


Acknowledgements

I acknowledge the many people who have helped make this thesis a reality.

Firstly, I acknowledge the efforts of my primary supervisor, Dr Suzi Edwards. Over the course of my PhD candidature, Suzi has been an ever present influence who has worked to ensure that this thesis is completed to the highest possible standard. Her knowledge of motion capture equipment, biomechanical data collection, data analysis, statistical analysis and writing skills that she has passed on have given me the ability to develop my own invaluable research skills. Suzi is the type of supervisor who will motivate you to produce high quality work and I thank her for her continued support.

I also thank my co-supervisors, Associate Professor Nicholas O'Dwyer and Dr Rene Ferdinands. Nick has provided an experienced eye, especially when constructing manuscripts that have helped to enhance my writing skills. Nick has also provided an alternative view of my fast bowling research to ensure that my research is clear and understandable to those unfamiliar with fast bowling research. I acknowledge Rene for his biomechanical knowledge of fast bowling and how best to interpret the data collected from this study. Rene also was a key figure in conducting the coaching intervention, which was a crucial aspect of this thesis.

I acknowledge Charles Sturt University (The School of Exercise Science, Sport and Health) and The University of Newcastle (School of Environmental and Life Sciences). I thank Charles Sturt University and staff for assisting me to complete my PhD and providing financial support. I also thank The University of Newcastle and their staff for allowing me access to their facilities to collect data using their biomechanics and musculoskeletal laboratories.

I also recognise the efforts of Trader Grenfell, Dr Phil Lucas and PRP Imaging. I acknowledge Trader who assisted in organising MRI scans across Sydney and the Central Coast so I could examine the spine health of participants. To Phil Lucas for providing
diagnosis and reports on the lumbar spine MRI scans and thank you to PRP Imaging for allowing me to use their facilities.

I acknowledge the following organisations: Cricket NSW, iCare NSW (formally Workcover NSW), Tumbi Umbi Sports and Wyong City Council. To Cricket NSW for supporting this project via partnership in the iCare grant and assisting with the recruitment of fast bowling participants to partake in this study. I acknowledge iCare for financial support to fund the MRI scans, accommodation and other costs associated with this study. To Tumbi Umbi Sports and Wyong City Council, we appreciated the provision of access to facilities to complete the coaching sessions as part of the intervention.

I recognise the efforts given by research assistants over the course of data collection for my PhD. To Matthew Cividin, Alex Pearson, Sam Treloar, John Brooks, Emma Reynolds and Sam White, I thank you for giving up your time to assist with laboratory and equipment setup, preparing participants and packing away of equipment. If there is anyone I have forgotten, I apologise but also thank you for your efforts.

As well, a big thank you to all the participants and their parents for taking the time to be a part of this study. Without participants within this research, this research would not be a reality and I hope you found your participation a rewarding experience. I realise in this busy world that attending multiple testing and coaching sessions can be difficult, so again thank you to participants and parents for finding the time.

Lastly, I thank my family and friends for the support given over the past few years. All the little things that you all have done throughout the last three and a half years is greatly appreciated and reminds me how lucky I am. To my partner, Stephanie, who has always been there for me. You have been a constant support to me, especially through stressful times and having to leave you for weeks at various times. I cannot begin to thank you enough.
Abstract

Background
Fast bowlers experience the highest incidence of injury in cricket, with most injuries occurring in the lumbar spine region attributed to aspects of fast bowling technique, such as the mixed action that displays greater shoulder counter-rotation. Coaching interventions afford a potentially valuable strategy whereby correction of the fast bowling technique has shown positive outcomes in reducing potential risk factors associated with lumbar spine injury.

Thesis Aim
The purpose of this thesis was to determine the biomechanical differences between the main action types and whether particular biomechanical bowling variables can account for lumbar spine abnormalities on diagnostic imaging in junior fast bowlers. A secondary aim was to explore a coaching intervention that targeted proposed biomechanical injury risk factor mechanisms for lumbar spine injury in junior fast bowlers.

Methods
Sixty junior district/zone (pre-state) male fast bowlers completed five consecutive overs across two cohorts. Three-dimensional kinematics and kinetics of the bowling action were recorded and analysed in Visual3D software. A randomly selected group completed a seven-week coaching intervention program. Magnetic resonance imaging (MRI) scans of the lumbar spine region were carried out pre-, mid- and post-season to monitor lumbar spine health.

Results
Significant differences affecting elbow, shoulder, trunk and pelvic angles between front-on, semi-open and mixed action types were observed. The mixed action displayed greater trunk rotation and higher thoraco-lumbar rotational range of motion during the back-foot contact phase. Significantly greater knee extension at ball-
release, hip internal rotation at arm-horizontal and reduced thoraco-lumbar range of motion were seen in the front lower-limb for participants with lumbar spine abnormality compared to the control group. Crunch factor analyses (trunk flexion/extension multiplied by pelvis rotation) were shown to be significantly correlated with increased L5-S1 and T12-L1 mediolateral shear force but reduced compressive force, but were not significantly linked with lumbar spine abnormality. The coaching intervention demonstrated that the coaching group demonstrated more positive improvements (45%) than the control group.

Conclusions

This thesis has shown that biomechanical differences exists between fast bowling action types, particularly in the mixed action during the back-foot contact phase. Due to the absence of differences in lumbar loading between actions during front-foot contact phase, lumbar region kinetics during back-foot contact phase need to be analysed in future research to determine if kinematic differences during this phase contribute to increased lumbar injury risk in junior fast bowlers. Traditional injury risk mechanisms were not associated with increased risk of lumbar spine injury. Rather, junior fast bowlers may be unable to dissipate load due to restricted thoraco-lumbar rotation and the motion of the front lower limb may affect injury risk via the inefficient transfer of load to the lumbar spine. Crunch factor was also found to be influential on lumbar load during fast bowling. This relationship may be detrimental to spinal health in junior fast bowlers as increased mediolateral shear joint force was associated with injury and requires further investigation. This thesis has also shown that a coaching intervention can reduce known injury mechanisms such as shoulder counter-rotation, shoulder-pelvis separation angle and trunk lateral flexion.
# Table of Contents

Dedication ..................................................................................................................i
Declaration ................................................................................................................... ii
Publications & Presentations ....................................................................................... iii
Acknowledgements ..................................................................................................... iv
Abstract ...................................................................................................................... vi
Table of Contents ........................................................................................................ viii
List of Tables ............................................................................................................... xii
List of Figures .............................................................................................................. xiv

**Chapter 1**  The Problem .......................................................................................... 17
  1.1 Introduction ........................................................................................................... 17
  1.2 Statement of the Problem ...................................................................................... 25
  1.3 Aims ...................................................................................................................... 26
  1.4 Research Hypothesis ............................................................................................ 26
  1.5 Limitations .......................................................................................................... 27
  1.6 Delimitations ...................................................................................................... 27
  1.7 References .......................................................................................................... 29

**Chapter 2** Mechanical differences between fast bowling action types in junior fast bowlers ......................................................................................................................... 34
  2.1 Abstract ................................................................................................................. 34
  2.2 Introduction ........................................................................................................... 35
  2.3 Methods ................................................................................................................. 38
    2.3.1 Participants ...................................................................................................... 38
    2.3.2 Experimental Protocol .................................................................................... 38
    2.3.3 Data Reduction ............................................................................................... 40
    2.3.4 Data Analysis .................................................................................................. 42
    2.3.5 Statistical Analyses ......................................................................................... 43
  2.4 Results .................................................................................................................. 45
    2.4.1 General Bowling Characteristics ...................................................................... 45
    2.4.2 Joint Angles .................................................................................................... 45
    2.4.3 Segment Alignment Angles .............................................................................. 49
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.4 Torso Joint Range of Motion</td>
<td>50</td>
</tr>
<tr>
<td>2.4.5 Trunk-Pelvis Angle and Segment Angles</td>
<td>52</td>
</tr>
<tr>
<td>2.4.6 Ground Reaction Force</td>
<td>53</td>
</tr>
<tr>
<td>2.4.7 Joint Moments and Forces</td>
<td>55</td>
</tr>
<tr>
<td>2.5 Discussion</td>
<td>57</td>
</tr>
<tr>
<td>2.6 Conclusion</td>
<td>60</td>
</tr>
<tr>
<td>2.7 Acknowledgements</td>
<td>61</td>
</tr>
<tr>
<td>2.8 References</td>
<td>62</td>
</tr>
<tr>
<td>Chapter 3 Biomechanical links between lumbar spine abnormality and junior fast bowling technique</td>
<td>65</td>
</tr>
<tr>
<td>3.1 Abstract</td>
<td>65</td>
</tr>
<tr>
<td>3.2 Introduction</td>
<td>66</td>
</tr>
<tr>
<td>3.3 Methods</td>
<td>68</td>
</tr>
<tr>
<td>3.3.1 Participants</td>
<td>68</td>
</tr>
<tr>
<td>3.3.2 Experimental Protocol</td>
<td>68</td>
</tr>
<tr>
<td>3.3.3 Data Reduction</td>
<td>70</td>
</tr>
<tr>
<td>3.3.4 Data Analysis</td>
<td>71</td>
</tr>
<tr>
<td>3.3.5 Magnetic Resonance Imaging (MRI)</td>
<td>72</td>
</tr>
<tr>
<td>3.3.6 Statistical Analysis</td>
<td>73</td>
</tr>
<tr>
<td>3.4 Results</td>
<td>74</td>
</tr>
<tr>
<td>3.4.1 Action Classification and Injury Status</td>
<td>74</td>
</tr>
<tr>
<td>3.4.2 Joint and Alignment Angles</td>
<td>74</td>
</tr>
<tr>
<td>3.4.3 Joint Range of Motion</td>
<td>77</td>
</tr>
<tr>
<td>3.4.4 Joint Velocity Peaks and Timing</td>
<td>78</td>
</tr>
<tr>
<td>3.4.5 Ground Reaction Forces and Loading Rate</td>
<td>78</td>
</tr>
<tr>
<td>3.4.6 Torso Joint Moments and Forces</td>
<td>81</td>
</tr>
<tr>
<td>3.5 Discussion</td>
<td>82</td>
</tr>
<tr>
<td>3.6 Conclusions</td>
<td>85</td>
</tr>
<tr>
<td>3.7 Acknowledgements</td>
<td>85</td>
</tr>
<tr>
<td>3.8 References</td>
<td>87</td>
</tr>
</tbody>
</table>
Chapter 4  ‘Crunch factor’ and the magnitude of its variability within the fast bowling action relationship to injury in junior fast bowlers. ........ 90
4.1 Abstract ........................................................................................................ 90
4.2 Introduction ................................................................................................... 91
4.3 Methods ........................................................................................................ 94
4.3.1 Participants ............................................................................................... 94
4.3.2 Experimental Protocol ............................................................................. 94
4.3.3 Data Reduction ......................................................................................... 96
4.3.4 Data Analysis ............................................................................................ 96
4.3.5 Magnetic Resonance Imaging .................................................................. 98
4.3.6 Statistical Analysis ..................................................................................... 99
4.4 Results .......................................................................................................... 101
4.4.1 Action Classification and LSA ................................................................. 101
4.4.2 Crunch Factor and Spinal Load ............................................................... 101
4.4.3 Crunch Factor and LSA ........................................................................... 107
4.4.4 Crunch Factor multiplied by Peak GRF ............................................... 108
4.4.5 Crunch Factor multiplied by Shoulder-Pelvis Separation Angle .. 109
4.4.6 Crunch Factor Variability and injury ................................................. 110
4.5 Discussion ..................................................................................................... 112
4.6 Conclusions ................................................................................................. 116
4.7 Acknowledgements ....................................................................................... 117
4.8 References ...................................................................................................... 118

Chapter 5  A proposed coaching model for the reduction of lumbar injury risk in fast bowling .......................................................... 122
5.1 Abstract ....................................................................................................... 122
5.2 Introduction .................................................................................................. 123
5.3 Methods ....................................................................................................... 126
5.3.1 Participants .............................................................................................. 126
5.3.2 Experimental Protocol ............................................................................ 127
5.3.3 Data Reduction ........................................................................................ 128
5.3.4 Data Analysis ........................................................................................... 129
5.3.5 Coaching Intervention Protocol ............................................................. 131
7.11 Glossary of Key Terms and Abbreviations ........................................... 209
7.11.1 Glossary ...................................................................................... 209
7.11.2 Abbreviations .............................................................................. 212
List of Tables

Table 2-1 Classification of fast bowling action types based on Ferdinands et al. (2014a). ................................................................. 43
Table 2-2 Results of general bowling characteristics between action types. .......45
Table 3-1 Distribution of action types for the non-injured and LSA group. .......74
Table 4-1 Definition of Thoraco-pelvic and Pelvic crunch factors using segment angular velocities. ........................................ 98
Table 4-2 Distribution of injury among action types for the non-injured and LSA group. ................................................................. 101
Table 4-3 Intra-subject coefficient of variations (%) of crunch factors (CF1-CF8) for non-injured (Non-Inj) and LSA groups. ................ 111
Table 5-1 Definition of crunch factors calculated using angular velocities. ...... 130
Table 5-2 Distribution of action types for the control and coaching groups. ...... 133
Table 5-3: Mean segment alignment angles, trunk angles, pelvis segment angles and ball speed of coaching group at pre- and post-intervention. .... 143
Table 5-4: Mean segment alignment angles, trunk angles, pelvis segment angles and ball speed of control group at pre- and post-intervention. ......... 144
Table 5-5: Breakdown of positive and negative changes for the coaching and control groups according to the results shown in Table 5-3 and Table 5-4. .... 145
Table 7-1 Distribution of action types for the running track and no running track groups. Percentage breakdown of total action types per group. .... 195
Table 7-2 Mean (± SE) of significant interactions for bowling arm joint angles between control and coaching groups. ............................... 200
Table 7-3: Attendance of coaching group for the seven sessions conducted. .... 208
List of Figures

Figure 2-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. .................................................................40

Figure 2-2 Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer et al., 2018, p.3). ..........41

Figure 2-3 Mean (± SE) values of nine lower limb joint angles at back-foot contact phase (BIC, A), and front-foot contact phase (FIC, B) across bowling action types and stages of the bowling action ..............................................47

Figure 2-4 Mean (± SE) values of six torso joint angles (A) and seven bowling arm joint angles (B) across bowling action types and stages of the bowling action .................................................................48

Figure 2-5 Mean (± SE) segment alignment angles across bowling action types .... 49

Figure 2-6 Mean (± SE) values of L5-S1 and T12-L1 joint range of motion (ROM) during back-foot contact phase (A) and front-foot contact phase (B) across action types ..............................................................................51

Figure 2-7 Mean (± SE) values of trunk-pelvis angles, pelvis segment angles and trunk segment angles across bowling action types and stages of the bowling action .................................................................52

Figure 2-8 Mean (± SE) values of peak GRF (relative BW) and FV loading rate (BW·s⁻¹) (A), impulse (relative BW) (B), and timing of peak GRF (s) (C) across bowling action types. .................................................................54

Figure 2-9 Mean (± SE) values of peak front lower limb (A), torso joint (B) moments (relative BM x height) and joint forces (C) (relative to BM) across bowling action types. .................................................................56

Figure 3-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. .................................................................70

Figure 3-2 Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer et al., 2017, p.3) ......... 71

Figure 3-3 Mean ± standard error (SE) of segment alignment angles for non-injured and LSA groups. .................................................................75

Figure 3-4 Mean (± SE) values of nine lower limb joint angles for front-foot contact phase (A), six torso joint angles (B) and trunk-pelvis angles, and pelvis and trunk segment angles (C) across stages of the bowling action for non-injured (Non-Inj) and LSA groups .................................................................76

Figure 3-5 Mean (± SE) values of L5-S1 and T12-L1 joint ROM from BIC to FIC (A) and FIC to BR (B) across non-injured and LSA groups. .................................................................77

Figure 3-6 Mean (± SE) values of peak torso joint velocity (A), and time to peak torso joint velocity (B) across non-injured and LSA groups .................................................................79
Figure 3-7 Mean (± SE) values of peak GRF (relative BW) and Fv1 loading rate (BW·s^{−1}) (A), impulse (BW·s) (B), timing of peak GRF (s) (C) between non-injured and LSA groups. ................................................................. 80

Figure 3-8 Mean (± SE) values of peak torso joint (A) moment (relative BM x height) and (B) force (relative BM) between non-injured and LSA groups. .................................................................81

Figure 4-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. ................................................................. 95

Figure 4-2 Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer et al., 2018) ................................................................. 97

Figure 4-3 CF1 (Trunk_{flex-ext}^{Trunk_{lat}} flex) (A), CF2 (Trunk_{flex-ext}^{Trunk_{lat}} Pelvic_{rot}) (B), CF3 (Trunk_{lat-ext}^{Trunk_{lat}} Pelvic_{rot}) (C) and CF4 (Trunk_{flex-ext}^{Trunk_{lat}} Pelvic_{rot}) (D) from BIC to AV. ................................................................. 102

Figure 4-4 Significant correlations of CF2 (Trunk_{flex-ext}^{Trunk_{lat}} Pelvic_{rot}) with L5-S1 mediolateral force at FV (A), L5-S1 compressive force at FIC-BR (B) & FV (C). ................................................................. 103

Figure 4-5 Significant correlations of CF2 (Trunk_{flex-ext}^{Trunk_{lat}} Pelvic_{rot}) with T12-L1 compressive force at FIC-BR (A), FV (B) & Sh-Pel Sep (C). ................................................................. 104

Figure 4-6 Significant correlations of CF2 (Trunk_{flex-ext}^{Trunk_{lat}} Pelvic_{rot}) with T12-L1 mediolateral force at FV (A) & Sh-Pel Sep (B). ................................................................. 105

Figure 4-7 Significant correlations of CF4 (Trunk_{flex-ext}^{Trunk_{lat}} Pelvic_{rot}) with T12-L1 compressive force at FIC-BR (A) & FV (B). ................................................................. 106

Figure 4-8 Mean (± SE) thoraco-pelvic (A) and pelvic (B) crunch factors for non-injured (Non-Inj) and LSA groups. ................................................................. 107

Figure 4-9 Mean (± SE) of combined crunch factors for peak GRF with thoraco-pelvic crunch factors (A) and pelvic crunch factors (B) for non-injured (Non-Inj) and LSA groups. ................................................................. 108

Figure 4-10 Mean (± SE) of combined crunch factors for peak shoulder-pelvis separation angle interaction with thoraco-pelvic crunch factors (A) and pelvic crunch factors (B) for non-injured (Non-Inj) and LSA groups. ................................................................. 109

Figure 4-11 Mean (± SE) variability for thoraco-pelvic (A) and pelvic (B) crunch factors for non-injured (Non-Inj) and LSA groups. ................................................................. 112

Figure 5-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. ................................................................. 128

Figure 5-2 Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer, et al., 2017, p.3). ................................................................. 129

Figure 5-3 Mean ± standard error (SE) of ball speed for control and coaching groups. ................................................................. 134

Figure 5-4 Mean (± SE) segment alignment angles (A) and values of six torso joint angles at AV (B) between control and coaching groups. ................................................................. 136
Figure 5-5  Mean (± SE) torso range of motion from BIC to FIC (A) and FIC to BR (B) between control and coaching groups. .................................................. 137

Figure 5-6  Mean (± SE) of ground reaction forces and loading rate (A), impulses (B) and timing (C) between control and coaching groups. ................................. 140

Figure 5-7  Mean (± SE) of torso joint moments (A) and torso joint forces (B) between control and coaching groups. ................................................................. 141

Figure 7-1  Mean (± SE) values of peak ground reaction forces between cohort 1-2 and cohort 3. .................................................................................. 195

Figure 7-2  Mean (± SE) values of 9 lower limb joint angles at back-foot contact phase (A) and 7 bowling arm joint angles (B) across stages of the bowling action and non-injured/LSA groups. ........................................ 197

Figure 7-3  Mean (± SE) values of peak lower limb joint moments (relative mass x height) for non-injured and LSA groups. ......................................................... 198

Figure 7-4  Mean (± SE) values of 9 lower limb joint angles at back-foot contact across stages of the bowling action and control and coaching groups. .......... 201

Figure 7-5  Mean (± SE) values of 9 lower limb joint angles at front-foot contact across stages of the bowling action and control and coaching groups. ........ 202

Figure 7-6  Mean (± SE) values of 6 torso joint angles at AV between control and coaching groups. .................................................................................. 203

Figure 7-7  Mean (± SE) values of trunk-pelvis angle across stages of the bowling action between control and coaching groups............................................ 204

Figure 7-8  Mean (± SE) values of peak torso joint velocity over 4 phases of the bowling action between control and coaching groups. .............................. 205

Figure 7-9  Mean (± SE) values of crunch factors over 5 phases of the bowling action between control and coaching groups.............................................. 206

Figure 7-10 Mean (± SE) values of peak lower limb joint moments (relative mass x height) between control and coaching groups. ................................. 207
Chapter 1: The Problem

1.1 Introduction

A team sport, cricket is the ninth most popular sport for junior males in Australia (Australian Bureau of Statistics, 2012) and is comprised of three main disciplines: batting, bowling and fielding. Fast bowling is a highly complex movement involving high-impact forces in an attempt to propel a cricket ball at high velocities towards the batter, which are known to exceed 140 km·h\(^{-1}\) at the elite level (Worthington, King, & Ranson, 2013b). To achieve a high ball velocity, fast bowling requires the coordinated movement of multiple body segments and interconnected joints to sustain high vertical ground reaction forces (up to 10 times body weight) at front-foot contact (Hurrion, Dyson, & Hale, 2000; Worthington, King, & Ranson, 2013a). Fast bowlers must repeat these high-impact loads six times each over, bowling an average of 4,052 deliveries throughout a season at senior state representative level (Dennis, Farhart, Goumas, & Orchard, 2002). As this high joint loading is repeated at such high frequency throughout the season, improper fast bowling technique may lead to injuries (Portus, Mason, Elliott, Pfitzner, & Done, 2004; Stuelcken, Ferdinands, & Sinclair, 2010).

Cricketer’s who specialise in fast bowling compared to other positions appear to be at the greatest risk of sustaining an injury (Stretch, 2003). When compared to other positions in cricket (batting, fielding, warming up or other cricket-related activities), fast bowlers experience higher rates of injuries in both senior and junior male divisions (Foster, John, Elliott, Ackland, & Fitch, 1989; Stretch, 2003), with up to 41% of all injuries throughout a season being attributed to fast bowling (Stretch, 2003). When injuries to fast bowlers are broken down by body region, the lumbar spine sustains the highest rates of injury compared to the limbs, trunk and head, ranging from a prevalence of 25% of players during a season to 70% over the course of a career (Annear, Chakera, Fosteran, & Hardcastle, 1992; Dennis, Finch, & Farhart, 2005b; Portus et al., 2004; Stretch, 2003; Stuelcken et al., 2010). Lumbar spine injuries often
consist of overuse conditions such as spondylolysis, spondylolisthesis, pedicle sclerosis, pars interarticularis and intervertebral disc degeneration, and they are hypothesised to result from the repetitive nature of fast bowling (Elliott, Hardcastle, Burnett, & Foster, 1992; Glazier, 2010). The prevalence of fast bowling injuries at the junior level is similar to that at the senior level, with as many as 52% of junior fast bowlers reporting lower back pain throughout a season (Dennis et al., 2005b). Even worse, 24.4% of junior fast bowlers display signs of lumbar disc degeneration (Elliott & Khangure, 2002). As the skeletal systems of junior athletes are still in development during the teenage years (Logsdon, 2007), the major concern is that the continued load on the lumbar spine during the fast bowling action may lead to serious long-term damage such as spondylolysis, spondylolisthesis and pedicle sclerosis, leading to thoracolumbar degenerative disease later in life (Annear et al., 1992).

Recent research into lumbar spine injury among fast bowlers has identified certain lumbar spine abnormalities such as bone oedema (accumulation of fluid) being linked to stress fractures in the lumbar vertebrae. Asymptomatic senior fast bowlers that display a lumbar bone oedema are highly likely to incur stress fractures to the lumbar vertebrae, suggesting bone oedema as a predictor of lumbar stress fractures (Kountouris, Portus, & Cook, 2012, 2013). The ability to predict stress fractures to the lumbar spine is of considerable importance as stress fractures lead to increased loss of game time (Orchard, James, & Portus, 2006). Kountouris et al. (2012 & 2013) has repeatedly found that 100% of participants demonstrating bone oedema at preseason went on to develop a stress fracture during the following season. Similarly, Ranson et al. (2008a) found that 70% of fast bowlers demonstrating a lumbar spine abnormality in a season would display a stress fracture in the next season. However, it is not yet understood the risk factors involved that contribute to the development of lumbar spine abnormalities such as bone oedema.

Currently, two risk factors, bowling workload (Orchard et al., 2015) and improper bowling technique (Elliott, 2000) have been identified as increasing the injury
incidence of lumbar spine injury in fast bowlers. The key injury preventative strategy to address the increased workload risk factor in the junior bowler is currently addressed by governing bodies in countries such as Australia, England and Wales by applying restrictions on the number of overs/balls that junior fast bowlers can bowl within a game and/or training. The guidelines proposed by the cricketing governing bodies set a maximum number of overs for junior fast bowlers during a spell within a match, as well as a limit on the total overs bowled per a match, according to age. These guidelines aim to limit the overall mechanical load during training, a spell and a game incurred by junior fast bowlers, in turn, suggested to lead to decreased lower injury risk in these junior bowlers. However, the maximum limit of overs bowled during a spell and/or total per match appears to have been selected arbitrarily with no scientific data supporting that these thresholds will reduce the risk of lumbar spine injury in youth bowlers. Research conducted on the changes in fast bowling technique during longer spells of bowling has shown limited changes in technique, minimal effects of fatigue and unaltered injury risk in elite senior fast bowlers (Portus, Sinclair, Burke, Moore, & Farhart, 2000) and junior fast bowlers (Burnett, Elliott, & Marshall, 1995; Crewe, Campbell, Elliott, & Alderson, 2013; Schaefer, O'Dwyer, Ferdinands, & Edwards, 2018). The commonly known fast bowling action types have been identified as the side-on, front-on, semi-open and mixed actions. Only the front-on action has been shown to change towards the end of the spell by moving to a mixed action (Burnett et al., 1995; Portus et al., 2000). However, due to the small sample sizes within these studies and the small distribution of the front-on action type within the bowling population, it is unclear whether this finding is of significance for injury risk. Therefore, these results of research into fast bowling during a spell discredit the need to restrict the amount of overs a junior bowler can perform. Examining the bowling workload of junior fast bowlers over a season has found that those who bowled more than 3,000 deliveries in an English season - more than the recommended guidelines - displayed lower rates of injury (33%) than those who bowled between 1,000 and 3,000
deliveries (37%) (Gregory, Batt, & Wallace, 2004). Therefore, the total workload may not be as crucial to injury risk among fast bowlers. Rather, the amount of rest between bouts of fast bowling may prove to be important in explaining injury risk. There is evidence to suggest that acute bouts of high bowling workload (more than 50 overs per match) at an elite level led to an increased risk of injury, which is delayed by up to three to four weeks (Orchard, James, Portus, Kountouris, & Dennis, 2009). It is unclear whether this finding of acute increase in bowling workload translates to junior athletes, further questioning the validity of the current guidelines for youth bowlers. Rather, these results emphasise the need to have bowlers maintain a consistent level of workload across a season. While recognised as an important factor to consider when examining lumbar spine injury risk, investigating bowling workload will be outside the scope of this thesis. Instead, this thesis will focus on fast bowling technique as the key risk factor influencing lumbar spine injury risk.

Improper bowling technique has been cited as a risk factor for fast bowlers developing lumbar spine injury (Elliott, 2000). Cricket fast bowling technique is commonly classified into four actions: side-on, front-on, semi-open and mixed action. The side-on, front-on and semi-open actions have been deemed to have a lower injury risk compared to the mixed bowling action (Bartlett, Stockill, Elliott, & Burnett, 1996). These three actions are thought to be safe due to the fact that the shoulders and hips remaining relatively aligned throughout the action (Bartlett et al., 1996; Elliott, 2000; Ferdinands, Kersting, Marshall, & Stuelcken, 2010a). In contrast, the mixed action combines aspects of the side-on and the front-on actions. In a mixed action the bowler begins with the chest facing towards the batsman at initial back foot-ground contact and then rotates the shoulder to a side-on alignment before ground impact of the front foot (Bartlett et al., 1996; Ferdinands et al., 2010a). This change in shoulder alignment away from the batsman between back foot- and front foot-ground contact is known as shoulder counter-rotation (Elliott, 2000). Various thresholds have been used to categorise excessive shoulder counter-rotation in the mixed bowling action, ranging
Chapter 1: The Problem

from 20° to 40° (Elliott, 2000; Ferdinands et al., 2010a; Foster et al., 1989; Ranson, Burnett, King, Patel, & O'Sullivan, 2008b). The mixed bowling action is common among the senior fast bowling population with up to 65% of bowlers utilising this action (Ferdinands et al., 2010a). Fast bowling technique research has typically concentrated on links with ball speed (Portus et al., 2004; Worthington et al., 2013b) and lumbar spine injury (Elliott, 2000; Glazier, 2010). Yet, little research exists on the biomechanical differences between the action types. Studies have examined segment alignment variables and the front knee angle in senior fast bowlers, finding increases in shoulder counter-rotation in front-on bowlers during 12-over and 8-over spells (Burnett et al., 1995; Portus et al., 2000). The studies by Burnett et al. (1995) and Portus et al. (2000) did not expand analysis to other biomechanical variables and had small samples (n = 9 and n = 14, respectively), which raises questions about the reliability of these studies results. A more substantial study on action types and kinematics of the lower trunk found no significant differences in lower trunk extension, contralateral side-flexion or ipsilateral rotation between mixed and non-mixed bowling actions among senior fast bowlers (Ranson et al., 2008b). However, the results of this study did not elaborate upon differences of the other known action types (Ranson et al., 2008b). Therefore, a gap in the research exists where the classification of action types is based on a few variables, yet little research exists that outlines a comprehensive 3D kinematic and kinetic biomechanical comparison of all fast bowling action types particularly in junior fast bowlers.

Key fast bowling technique biomechanical characteristics previously identified to be linked with lumbar spine injury risk have included shoulder counter-rotation, trunk lateral flexion, shoulder-pelvis separation angle, front-knee angle and increased lumbar loading. As mentioned previously, shoulder counter-rotation is the key factor distinguishing the mixed action with other actions and is a critical variable connected to increased risk of injury (Elliott, 2000; Foster et al., 1989; Portus et al., 2004). This twisting motion of the shoulder counter-rotation during fast bowling may explain why
Chapter 1: The Problem

Fast bowlers are particularly prone to lumbar spine injury. It has been shown that a shoulder counter-rotation from 20° (Elliott & Khangure, 2002) to 40° can increase the risk of lumbar spine injury such as stress fractures (Foster et al., 1989; Portus et al., 2004). The higher risk of lumbar spine injury may be due to greater shoulder counter-rotation being linked to higher lumbo-pelvic loading (Crewe et al., 2013; Ferdinands, Stuelcken, Greene, Sinclair, & Smith, 2010b). The movement of the trunk and pelvis is of importance when examining lumbar spine injury risk in fast bowlers. Increased lateral flexion of the trunk away from the bowling arm has been attributed to lower back pain in fast bowlers (Stuelcken et al., 2010). Shoulder-pelvis separation, the angle between the shoulders and pelvis, has been linked to soft tissue injury and thought to place the lumbar spine under greater torsional stress (Portus et al., 2004). The motion of the front knee also plays a role in ground reaction force production and injury. A more flexed knee is associated with reduced magnitudes of peak ground reaction forces and injury risk when the front knee is more flexed at the commencement of a season among senior fast bowlers (Ferdinands et al., 2010b; Olivier, Stewart, Green, & McKinon, 2015). When performing the fast bowling action the lumbar spine sustains large amounts of strain contributing to the likelihood of injury. It been reported that junior fast bowlers produce high lumbo-pelvic loads (peak joint moments; flexion: 10.4±5.3 Nm·kg⁻¹·m⁻¹; rotation: 10.1±3.5 Nm·kg⁻¹·m⁻¹; lateral bending: 12.4±4.3 Nm·kg⁻¹·m⁻¹), which typically occur when vertical ground reaction forces are the highest (Crewe et al., 2013; Ferdinands, Kersting, & Marshall, 2009). Subjecting the spine to maximum ranges of motion in all three planes of motion increases the likelihood of injury due to the higher loading sustained (Costi et al., 2007; Drake, Aultman, McGill, & Callaghan, 2005; Shirazi-Adl, Ahmed, & Shrivastava, 1986). This is reflected in fast bowling where greater movement in multiple planes of the trunk and pelvis has been related to increases in lumbo-pelvic torque and anterior-posterior shear joint forces (Crewe et al., 2013; Ferdinands et al., 2010b). While many factors associated with fast bowling action have been put forth to explain lumbar spine injury risk, with the
exception of shoulder counter-rotation, no thresholds have been proposed to demark when injury risk is significantly increased.

The multi-planar movement of many sporting activities has led to the recent development of ‘crunch factor’ as a potential mechanism to explain lumbar spine injury. Crunch factor was first defined as the product of simultaneous lateral bending and rotation angular velocities of the trunk (Sugaya, Morgan, & Banks, 1996) but has since been expanded to include other body segments or multiple segment combinations (Ferdinands, Kersting, & Marshall, 2014b; Glazier, 2010; Portus, Elliott, Lloyd, Galloway, & Timms, 2017). When applied to golf, greater crunch factor has been associated with increased compressive and shear joint forces from the downswing through to follow-through (Ferdinands et al., 2014b; Morgan, Cook, Banks, Sugaya, & Moriya, 1999). Crunch factor analysis has been proposed as a measure of lumbar spine injury risk in fast bowling (Glazier, 2010), as fast bowling demonstrates similar multi-planar movements seen in golf. Recent research into crunch factor analysis during fast bowling found no significant links between increased crunch factor of the trunk and lumbar spine injury (Portus et al., 2017). The authors only utilised single-segment crunch factors and suggested that the high variability of the crunch factor is likely to confound any potential relationship with injury and crunch factor. Further investigation into crunch factor analysis using multiple segments, similar to that of Ferdinands et al. (2014b), is required to ascertain the multi-segment interaction of the movement of the trunk and pelvis as a predictor of lumbar loading and injury risk.

An injury preventative strategy employed to reduce lumbar spine injury risk through technique modification is the use of a coaching intervention. The aim of technique modification is to typically change a fast bowler’s action from a mixed action to a more side-on or front-on action. By coaching a bowler to become more side-on/front-on and reduce the amount of shoulder counter-rotation in their action, the fast bowler can possibly reduce their risk of developing lumbar spine injury (Bartlett et al., 1996). A coaching intervention on junior fast bowlers (13.4 yr) during a four-year period
instructed participants to adopt a side-on action or front-on action (Elliott & Khangure, 2002). The intervention was successful in decreasing shoulder counter-rotation from $35 \pm 13^\circ$ to $21 \pm 9^\circ$ resulting in fewer participants with a mixed bowling action (81% to 33%) (Elliott & Khangure, 2002). The study did not employ a control group, with the authors citing that the level of lumbar disc degeneration would increase with age if no changes in shoulder counter-rotation are made (Elliott & Khangure, 2002). Another coaching intervention on older fast bowlers (18.5 ± 2.3 yr) during a two-year period also aimed to reduce shoulder counter-rotation along with other fast bowling biomechanical factors (Ranson, King, Burnett, Worthington, & Shine, 2009). The other biomechanical factors included shoulder alignment, trunk angles and knee angles (Ranson et al., 2009). This intervention was also successful in reducing shoulder counter-rotation as well as shoulder alignment at back-foot contact but knee or trunk angles were unaltered by coaching in this cohort of fast bowlers (Ranson et al., 2009).

Neither of these previous studies adopted a control group, with Elliott and Khangure (2002) citing that no changes in shoulder counter-rotation would lead to continued injury risk, whereas Ranson et al. (2009) had participants who did not receive coaching for a particular biomechanical variable (e.g. shoulder counter-rotation) act as a control for the participants who did receive coaching in that same variable. An alternative coaching intervention by Wallis, Elliott, and Koh (2002) utilised a harness as an external constraint to control the fast bowling action in junior fast bowlers (13 yr). The aim of this intervention was to use a harness to connect to the shoulders and hips to restrict shoulder counter-rotation, shoulder-pelvis separation and lateral trunk flexion during the delivery stride over an eight-week period. When the harness was worn, the authors observed a decrease in shoulder counter-rotation, however, when the harness was removed from the bowler no significant changes were seen in their technique over the short term. Nevertheless, coaching interventions appear to be a viable method for reducing the magnitude of shoulder counter-rotation leading to a potential decrease in lumbar spine injury risk. However, a randomised-controlled trial coaching
intervention study that can reduce shoulder counter-rotation, as well as other key biomechanical factors during fast bowling is needed to confirm whether coaching is an effective method of lowering injury risk.

1.2 Statement of the Problem
Male junior fast bowlers experience higher injury rates, specifically of the lumbar spine region, than players of any other playing position in cricket (Stretch, 2003). To prevent lumbar spine injury in junior bowlers, two injury prevention strategies have been identified: bowling technique modification through coaching interventions, and restriction on bowling workload (maximum number of deliveries by junior fast bowlers during games and training). Currently, there is conflicting evidence showing that restricting workload alone is effective in decreasing injury risk. Greater understanding of biomechanical fast bowling risk factors and coaching interventions is required to reduce lumbar spine injury risk. To date, a dearth of scientific literature exists exploring biomechanical differences between the known fast bowling action types. Initial investigations into links between fast bowling technique and lumbar spine injury have made progress, yet further research is required to identify a definitive injury mechanism. As fast bowling technique has been implicated in lumbar spine injury risk, research needs to target junior fast bowlers, to make corrections to their bowling technique at a younger age. Therefore, any improvements made to fast bowling technique during these junior years has the potential to decrease their lumbar spine injury risk, leading to greater adaptation to increased fast bowling workload in senior years. Alternative mechanisms of lumbar spine injury are also worth exploring to evaluate the relationship of the 3D motion between the trunk and pelvis during the fast bowling action. It is also necessary to establish and assess the ability of coaching interventions to change a variety of biomechanical risk factors during the fast bowling action and reduce lower lumbar spine injury risk in cricket fast bowlers.
1.3 Aims

The purpose of this thesis was to:

a) Determine if there were any significant differences between action type mechanics in junior fast bowlers.

b) Determine the key biomechanical risk factors during junior fast bowling related to lumbar spine abnormalities (LSAs).

c) Investigate the relationship between lumbar spine loading and abnormalities with multi-segment crunch factor analyses and magnitude of crunch factor variability of the junior fast bowling action.

d) Determine whether a randomised-controlled seven-week coaching model would alter technical characteristics of the junior fast bowling technique that have been previously associated with lumbar spine injury.

1.4 Research Hypothesis

It was hypothesised that:

a) Junior fast bowlers with different action types would employ kinematic and kinetic strategies that may be linked with injury risk;

b) Asymptomatic junior fast bowlers with LSAs would demonstrate greater shoulder counter-rotation, shoulder-pelvis separation angle, trunk lateral flexion, front knee extension and lumbar loading than those without an LSA;

c) Crunch factors would be positively correlated with spinal joint moments and forces, while junior fast bowlers with a LSA would present with greater crunch factor and low crunch factor variability; and

d) The coaching intervention would reduce fast bowling risk factors associated with lumbar spine injury risk in junior fast bowlers.
1.5 Limitations

It is acknowledged that the following factors may limit the results of this thesis:

a) Participants may have altered their bowling technique due to performing in a laboratory-based environment, as opposed to a game situation;
b) Although being classified as fast bowlers at a representative level, current fitness levels, skill and training status may have varied between the participants who were recruited, thereby increasing the possibility of participant heterogeneity;
c) The use of computerised data recording equipment to collect 3D motion data carries a level of measurement error, which was reduced using 3D marker-based systems and reducing skin artefact motion:
d) Each participant was allowed a self-selected bowling run-up distance and speed, so that the approach speed for each participant was not standardised;
e) Adherence to the study program, including repeated biomechanical assessments, MRI appointments and the seven-week coaching program, could not be guaranteed due to unforeseeable conflicting appointments, drop-out and/or injury; and
f) Participants were unable to wear shoes fitted with spikes on the soles during testing in the laboratory, reducing the grip that participants may be accustomed to when bowling in an outdoor game situation.

1.6 Delimitations

The following factors delimited this study:

a) The sample selected only included junior male fast bowlers, implying that the results obtained from this study may not be a true reflection of the entire fast bowling population (adult and female);
Chapter 1: The Problem

b) The sample selected for this study was restricted to Australian participants (New South Wales) and did not include fast bowlers from other cricket playing nations;

c) Participants were only tested on a standard stock delivery and were required to satisfy line and length guidelines;

d) Participants bowled in a controlled laboratory environment with a set temperature, humidity and no other team members or crowds present; and

e) All marker positioning on the participants was completed by the primary investigator to ensure reliability of results.
1.7 References


Chapter 1: The Problem


Chapter 1: The Problem


Chapter 1: The Problem


Context of Manuscript in Relation to the Thesis

The first manuscript of this thesis attempts to provide a comprehensive three-dimensional (3D) analysis of the four known fast bowling action types in junior fast bowlers. This manuscript will provide a 3D fast bowling biomechanical analysis in order to compare the differences in the fast bowling action types in junior athletes, which has received limited research previously. Any differences outlined here may offer insights into future areas of research to relate fast bowling technique with lumbar spine injury and bowling performance in junior bowlers.
Chapter 2  Mechanical differences between fast bowling action types in junior fast bowlers

This chapter is an amended version of the manuscript: Schaefer, A., Ferdinands, R. E. D., O’ Dwyer, N., & Edwards, S. Mechanical differences between fast bowling action types in junior fast bowlers. To be submitted to the Journal of Biomechanics.

2.1  Abstract

Background: Fast bowling technique is categorised into four action types: side-on, front-on, semi-open and mixed. The mechanics of these different actions are thought to be highly relevant to lumbar spine injuries, yet there is no biomechanical comparison between action types in junior fast bowlers.

Aim: This study aimed to determine if there were any significant differences between action type mechanics in junior fast bowlers.

Methods: A comprehensive 3D motion analysis of 60 junior male fast bowlers who bowled a five-over spell at competition pace was performed. Kinematic and kinetic data were collected for rear-leg, front-leg, trunk and bowling arm during the bowling action. Bowlers were classified into side-on (n = 2), front-on (n = 14), semi-open (n = 18) and mixed (n = 26) action groups using shoulder counter-rotation. Mixed modelling factorial analyses of variance was used to determine between-group differences.

Results: Significant differences affecting 12 elbow and shoulder joint, trunk and pelvic segments variables were observed between front-on, semi-open and mixed action groups. The mixed action bowlers displayed higher T12-L1 (thoraco-lumbar) rotation compared to semi-open bowlers (-15±2° and -6±2° respectively), particularly at back-foot initial contact and higher thoraco-lumbar rotational range of motion compared to front-on and semi-open bowlers (36±3°, 27±4° and 25±3° respectively) between back-
foot and front-foot contact. The only kinetic between-group difference was higher vertical ground reaction force loading rate of mixed and front-on bowlers compared to semi-open bowlers.

**Conclusions:** As expected, the mixed action displayed higher trunk segment angles and thoraco-lumbar joint angle rotation at back-foot initial contact phase than the other action types. The absence of significant between-group differences in spinal loading during front-foot contact phase suggests that fast bowlers attenuate forces at similar rates in spite of action type differences to attain similar ball speeds and this may not influence lumbar spine injury risk. This warrants the urgent analysis of spinal kinetics during back-foot contact phase to establish whether differences in kinematics during this phase result in increased performance and/or lumbar injury risk in junior fast bowlers.

### 2.2 Introduction

Fast bowlers aim to release a cricket ball at the maximum possible speed towards the batsman, with elite male fast bowlers achieving ball speeds in excess of 140 km·h$^{-1}$ (Worthington et al., 2013b). To generate such high ball speeds, fast bowlers are forced to load the lumbar spine over a short period (Ferdinands et al., 2009; Hurrion et al., 2000). This high rate of loading is believed to be a factor in the high prevalence of lumbar spine injuries amongst the senior fast bowling population (Dennis et al., 2002; Stretch, 2003). Increased rates of lumbar loading/injury have been linked to several kinematic aspects of the fast bowling technique, including the front-knee angle, pelvic and trunk rotation, and shoulder counter-rotation (Crewe et al., 2013; Elliott, 2000; Ferdinands et al., 2010b). Therefore, kinematic variables such as shoulder counter-rotation have been utilised to inform the development of classification systems for fast bowling action types.

Fast bowling actions are traditionally categorised into four broad fast bowling action types: side-on, front-on, semi-open and mixed, based on specific kinematic variables.
Chapter 2: Manuscript 1

These variables include shoulder alignment at back-foot contact, shoulder counter-rotation and shoulder-pelvis separation angle (Ferdinands et al., 2010a). The action type associated with the lowest rate of injury to the lumbar spine is the side-on action, which is characterised by the back foot contacting the ground parallel to the wicket and the body positioned so that the leading shoulder is directed down the line of the pitch (Bartlett et al., 1996). In the side-on action, shoulder alignment and counter-rotation are restricted to less than $25^\circ$ and $30^\circ$, respectively (Ferdinands et al., 2010a). Classification of the front-on action is based on the back foot landing in line with the pitch and the alignment of the shoulders being closer to parallel with the wicket (Bartlett et al., 1996), while shoulder alignment and counter-rotation are $>50^\circ$ and $<30^\circ$, respectively (Ferdinands et al., 2010a). In the semi-open action, back-foot shoulder alignment between $25^\circ$ and $50^\circ$ and shoulder counter-rotation $<30^\circ$ are used to classify the action (Ferdinands et al., 2010a; Portus et al., 2004).

The mixed action appears to place fast bowlers at highest risk of injury. This action type is characterised by the trunk beginning in a front-on position, before moving towards a more side-on position, thereby resulting in excessive shoulder counter-rotation (Elliott, 2000; Ferdinands et al., 2010a; Portus et al., 2004). The threshold of shoulder counter-rotation used to define the mixed bowling action has varied over time, ranging from $40^\circ$ (Foster et al., 1989) to $20^\circ$ (Elliott, 2000) or $30^\circ$ (Ranson et al., 2008), dependent on subsequent studies determining a new demarcation point between non-injured and injured groups of bowlers.

A number of studies have found that the mixed action is the most common bowling action, its percentage per bowling population varying from 44% to 80% in junior and senior fast bowlers (Burnett et al., 1995; Elliott and Khangure, 2002; Ferdinands et al., 2010a; Portus et al., 2004). The front-on action shows varying rates of distribution of 0% to 33% among junior and senior fast bowlers (Burnett et al., 1995; Portus et al., 2004). Studies into the distribution of the semi-open action have found low levels, with only 18% of senior fast bowlers using this action (Ferdinands et al., 2010a; Portus et
The distribution of side-on actions has also been shown to be low with 15% to 22% of junior and senior fast bowlers using this action, respectively (Burnett et al., 1995; Ferdinands et al., 2010).

There have been few investigations into the biomechanical differences that underlie the fast bowling action types. Recent research has focused on finding correlations of fast bowling technique with ball speed (Portus et al., 2004; Worthington et al., 2013b) and lumbar spine injury (Elliott, 2000; Glazier, 2010). Two studies have examined segment alignment variables and the front knee angle in junior and senior fast bowlers, but neither study expanded their analysis to other biomechanical variables (Burnett et al., 1995; Portus et al., 2000). While the studies by Burnett et al. (1995) and Portus et al. (2000) found increases in shoulder counter-rotation in front-on bowlers during 12-over (junior) and eight-over (adult) spells respectively, the small samples (n = 9 and n = 14, respectively) pose the question of the reliability of these results. In contrast, a recent study of 25 junior fast bowlers (semi-open: n = 10, mixed: n = 9, front-on: n = 5, side-on: n = 1) found no substantial changes during a 10-over spell in mean values or variability of a comprehensive set of kinematic, kinetic and performance variables, which instead revealed a high degree of consistency in kinematic and kinetic patterns (Schaefer et al., 2018). A study of the relationship between fast bowling technique and the kinematics of the lower trunk in 50 senior fast bowlers (23 ± 4 yr) found no significant differences in lower trunk extension, contralateral side-flexion or ipsilateral rotation between mixed and non-mixed bowling actions (Ranson et al., 2008). Yet no research exists which outlines a thorough examination of these differences in action types.

Given the lack of research on biomechanical differences between action types in junior fast bowlers, the purpose of the current study was to examine a large sample size of junior fast bowlers to provide a comprehensive comparison between the known action types using three-dimensional kinematic and kinetic variables. It was hypothesised that
junior fast bowlers with different action types would show different kinematic and kinetic characteristics that may be linked with injury risk.

2.3 Methods

2.3.1 Participants

Sixty junior male fast bowlers (mean age = 14.6 ± 1.4 yr, height = 1.76 ± 0.1 m, mass = 64.5 ± 11.9 kg) were recruited from local district and zone level representative teams within New South Wales, across three separate cohorts (n = 60) from 2013-2015. Participants were aged between 12 and 18 years, free of injury and back pain during the time of testing, and classed as a fast bowler by the director of coaching for their district. Written informed consent was obtained from each participant and his parent/guardian prior to data collection and all methods were approved by the institution’s Human Research Ethics Committee (2013/062; 2014/169; H-2015-0059).

2.3.2 Experimental Protocol

The participants’ height, body mass, and trunk and pelvis dimensions were measured first for later use in the biomechanical model. The participants were then prepared for a static standing trial in the anatomical position. A standardised warm-up of balance and postural stability exercises was performed (Bird and Stuart, 2012), followed by six warm-up deliveries at half-pace in order to familiarise the participants to the laboratory environment. A five-over spell of bowling was then performed, taking ~1 hour to complete.

The participants bowled at competition pace (self-paced and self-selected run-up distance from the crease line) on a track measuring the same length as a standard cricket pitch (20.12 m), attempting to land the ball at a target on the ground 6-8 m from the stumps at the batsmen’s end. Pre-delivery approach speed for each participant was measured by placing two infrared timing gates (Speed Light, Swift Sports Equipment, Lismore, Australia; or Smart Speed, Fusion Sport, Summer Park,
Australia) 2 m apart at the point just before back-foot initial ground contact during the pre-delivery stride as a measure of bowling performance. In order to replicate match conditions, there was a non-bowling period of ~4·5 mins between each over according to the protocol of Schaefer et al. (2018).

Whole body motions of the participants were recorded using a motion capture system (500 Hz; Qualisys AB, Göteborg, Sweden) with 12 (cohort 1) or 14 (cohort 2) Oqus 300+ cameras, or 15 (cohort 3) Oqus 700+ cameras. Passive reflective markers (15mm) were placed on specific locations on each of the lower and upper limbs, pelvis, torso, head and lower back (Figure 2-1). These marker locations included makers on the lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, the ribcage bilaterally at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker and the lumbar segment (five tracking cluster markers) according to Schaefer et al. (2018) and Crewe et al. (2013). Three markers were also placed in one side of the cricket ball in a triangular configuration. In order to minimise the risk of losing the view of the reflective markers and avoid putting markers on clothes, the participants wore minimal clothing (shorts) with their own socks and athletic shoes.
Figure 2-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. Static markers were used for the static trial and removed for dynamic trials (including L-R 1st metatarsal, L-R medial malleolus, L-R medial femoral epicondyle) (Schaefer et al., 2018, p.10).

The 3D ground reaction forces (GRFs) were measured using two multichannel force platforms (2,000 Hz; Type 9281CA and 9281EA, Kistler, Winterthur, Switzerland), for the front-foot contact phase only. The force platforms were embedded in the floor and connected to control units (Type 5233A and Type 5606, Kistler, Winterthur, Switzerland). For cohorts 1 and 2, the force platforms and run-up track were covered with a 20 mm polyurethane athletic track surface. While for cohort 3, the force plates had no added surface and had a concrete run-up track. As the between-cohort differences in surfaces was thought to a possible confounding effect, appropriate steps were taken to ensure there was correct force plate definition and GRF vector location (see Appendix 7.8.1, Figure 7-1 for cohort differences). The 3D data were recorded for every delivery (30 ball deliveries) in the five-over spell.

2.3.3 Data Reduction

For the kinematic and kinetic data used for analysis, the following temporal stages of the bowling action were defined automatically and confirmed by visual inspection: back-foot initial foot-ground contact (BIC), front-foot initial foot-ground contact (FIC),
the times of peak vertical ($F_v$), GRF, bowling upper-arm horizontal backwards (AH), ball release (BR), bowling upper-arm vertically downwards (AV), and front-foot alignment (Figure 2-2) (Schaefer et al., 2018). Once the temporal stages have been established, all joint angles, trunk and pelvis segment angles were quantified at these stages. The back-foot contact phase is defined from BIC to FIC, whereas the front-foot contact phase is defined from FIC to AV. Segmental angles that included pelvic and shoulder alignment (relative to the laboratory), pelvic and shoulder counter-rotation and shoulder-pelvic separation angle at the time of BIC and FIC were defined according to Ferdinands et al. (2010a). Shoulder and pelvis counter-rotation were calculated as shoulder and pelvis alignment at BIC minus peak shoulder and pelvis alignment, respectively.

![Figure 2-2](image)

**Figure 2-2**  Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer et al., 2018, p.3).

All six balls from each of the five overs (30 trials) were selected for 3D kinematic and kinetic analyses, which were performed with Visual3D software (Version 5, C-Motion, Germantown, MD). Prior to establishing the temporal stages of the bowling action, raw kinematic, GRF, moment and centre of pressure data were low-pass filtered (Butterworth digital, fourth-order zero-phase with $f_c = 18$ Hz) before the calculation of individual joint kinematics and net internal joint moments and forces during front foot-ground contact of the bowling action (Bisseling and Hof, 2006). Calculation of peak magnitudes and loading rates of GRFs were performed on the raw GRFs that were low-pass filtered at 50 Hz (Butterworth digital, fourth-order zero-phase) using a
customised LabView program (LabView, 2010, National Instruments Corporation, Austin, TX, USA).

Segment masses and inertial properties, and Cartesian local coordinate system and sequence of rotation were defined according to Schaefer et al. (2018). An x,y,z Cardan sequence of rotation for trunk-pelvis joint angles were expressed as extension-flexion, right-left lateral flexion and left-right rotation. The pelvis and trunk segment angles were evaluated by absolute angle (relative to the laboratory) in all three planes and expressed as extension-flexion, right-left lateral flexion and left-right rotation. Joint ranges of motion (ROM) for L5-S1 and T12-L1 were calculated as the difference between peak maximum and minimum joint angles. The ROMs were then calculated for the phases of BIC-FIC and FIC-BR. Ball speed was calculated by calculating the resultant distance the ball travelled from frame one to frame five after ball-release, and then divided by this time period.

2.3.4 Data Analysis

Net internal joint forces and moments were estimated via inverse dynamics and peak GRF variables were calculated between FIC and AV. In line with the majority of previous research that has measured kinetics during the front-foot contact phase when the GRFs are highest and injury risk is thought to be increased (Crewe et al., 2013; Ferdinands et al., 2009; Portus et al., 2004; Worthington et al., 2013a), kinetic variables were computed during front-foot contact phase only. Kinetic variables were excluded from statistical analysis when the front foot missed or only partially contacted the force platforms (Unsuccessful trials: cohort 1 = 15.8 ± 15.0%, cohort 2 = 13.7 ± 15.6, and cohort 3 = 24.9 ± 15.4%). L5-S1 and T12-L1 joint forces were normalised to body weight (relative BW) and peak net internal joint moments were normalised to the participant’s body mass multiplied by height (relative BM x height). Both GRFs and joint loading variables were included within this analysis in light of the fact that researchers often incorrectly assume that GRF variables indicate joint loadings (Edwards et al., 2014).
Each participant’s fast bowling action was classified into either side-on, front-on, semi-open or mixed as defined by Ferdinands et al. (2014), using shoulder counter-rotation only. The classifications were based on the segment angles taken by 3D motion capture (Table 2-1). While this classification protocol breaks down the mixed bowling action into 15 sub-categories, only the four primary categories (side-on, front-on, semi-open and mixed) were used here, since analysing all 15 sub-categories would require a more substantial sample size than available here.

Table 2-1 Classification of fast bowling action types based on Ferdinands et al. (2014a).

<table>
<thead>
<tr>
<th>Action type</th>
<th>Shoulder Alignment at BIC</th>
<th>Shoulder Counter-rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-on</td>
<td>&lt;25°</td>
<td>&lt;40°</td>
</tr>
<tr>
<td>Front-on</td>
<td>≥50°</td>
<td>&lt;40°</td>
</tr>
<tr>
<td>Semi-open</td>
<td>25° ≤ and &lt;50°</td>
<td>&lt;40°</td>
</tr>
<tr>
<td>Mixed</td>
<td>N/A</td>
<td>&gt;40°</td>
</tr>
</tbody>
</table>

2.3.5 Statistical Analyses

Means and standard deviations (SDs) were calculated for all variables for all overs. A series of mixed-design factorial analyses of variance (ANOVAs) were used to determine significant changes (P<0.05) in the means across all variables. When significant effects were found, Tukey post hoc tests were conducted to identify their precise locus. All ANOVAs were carried out using Statistica (v.10, StatSoft Inc., Tulsa, OK, USA). Outcome variables were split into the following categories for the primary test of the effect of the four bowling action types: ball speed, joint angles, segment alignments, joint forces, trunk-pelvis angle, trunk segment angle, pelvis segment angle, ROMs and GRFs.

Three factors were used for analyses of joint angles (stages*angles*actions), trunk-pelvis angles (stages*angles*actions), trunk segment angles (stages*angles*actions), and pelvis segment angles (stages*angles*actions). The angles encompassed the 22 joint angles, three trunk-pelvis angles, three trunk segment angles and three pelvis segment angles, measured at the stages of the fast bowling action. The stages of the
bowling action encompassed the six critical time points of the bowling action: BIC, FIC, FV, AH, BR and AV. Different stages were compared depending on the angles involved. The torso (L5-S1 and T12-L1) joint angles, trunk-pelvis angles, trunk segment angles and pelvis segment angles were compared across all six stages. As the lower limbs are not in contact with the ground during all the stages, the back-foot lower limb angles (ankle, knee and hip) were compared across BIC and FIC, while the front-foot lower limb angles (ankle, knee and hip) were compared across FIC, FV, AH, BR and AV.

There were two factors for analyses of GRFs (impulses*actions; forces*actions; timing*actions), joint forces (joints*actions), alignment angles (align*actions), anthropometrics/approach speed (anthro*actions) and joint ROM (ROM*actions). There was one factor (actions) for analyses of the measures of bowling speed and the vertical GRF loading rate. To report the effect sizes of the interactions of the repeated measures ANOVAs partial eta squared were employed. Effects sizes ($\eta^2_p$) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson, 2011).

The data were first checked to ensure that they satisfied the assumptions of normality of distribution and sphericity. To check the assumptions of normality of distribution, all data was placed into histograms and visually inspected to ensure normal distribution. When these assumptions were violated, multivariate ANOVAs were used. Residuals were examined to test the assumption of constant variance and normality by placing residual data into scatterplots and visually inspecting for outlying data, which were both accepted. One participant was excluded from analysis because they released the ball between back-foot initial contact and front-foot initial contact, an action substantially different to the traditional action in which the bowler releases the ball from the front-foot contact, potentially confounding the results.

It was to be expected that the outcomes variables (ball speed, joint angles, segment alignments, joint forces, trunk-pelvis angle, trunk segment angle, pelvis segment angle, ROMs and GRFs) would vary significantly across the stages of the bowling action.
Similarly, significant differences were to be expected between the variables within each category of the outcome variable. For example, differences would be expected between joint angles and between segment alignments. Such differences, however, were not relevant to the primary hypotheses concerning the effects of type of fast bowling action. Therefore, only main effects or interactions that involved the factor of bowling action type (actions) were reported here.

2.4 Results

2.4.1 General Bowling Characteristics

There was no significant main effect of action type on anthropometrics/approach speed \( (F_{2,51} = 0.59, P = 0.56, \eta^2_p = 0.0226) \), nor any significant interaction of anthro*action types \( (F_{6,153} = 0.38, P = 0.89, \eta^2_p = 0.0147) \). The distribution of bowling actions within the 60 participants was 43.3% \( (n = 26) \) mixed, 30.0% \( (n = 18) \) semi-open, 23.3% \( (n = 14) \) front-on and 3.3% \( (n = 2) \) side-on. The side-on action was removed from further statistical analysis due to low sample size. No significant differences were observed for the main effect \( (F_{2,54} = 0.14, P = 0.87, \eta^2_p = 0.0052) \) or interactions between speed*action types for mean ball speed \( (F_{2,54} = 0.14, P = 0.87, \eta^2_p = 0.0052) \). The results comparing the general bowling characteristics between the action types are located in Table 2-2.

<table>
<thead>
<tr>
<th>Action type</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Ball Speed (km/h)</th>
<th>Approach Speed (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front-on</td>
<td>15.2 ± 0.4</td>
<td>179.3 ± 2.6</td>
<td>67.7 ± 3.1</td>
<td>87.6 ± 2.2</td>
<td>0.37 ± 0.01</td>
</tr>
<tr>
<td>Mixed</td>
<td>14.3 ± 0.3</td>
<td>175.9 ± 1.9</td>
<td>64.3 ± 2.3</td>
<td>86.5 ± 1.6</td>
<td>0.37 ± 0.01</td>
</tr>
<tr>
<td>Semi-open</td>
<td>14.5 ± 0.3</td>
<td>176.8 ± 2.3</td>
<td>66 ± 2.7</td>
<td>86.0 ± 1.9</td>
<td>0.40 ± 0.01</td>
</tr>
</tbody>
</table>

2.4.2 Joint Angles

While there was no main effect of action type \( (F_{2,54} = 2.9, P = 0.06, \eta^2_p = 0.0981) \), a significant three-way interaction of stages*angles*actions interaction was observed for
back-foot lower limb joint angle values ($F_{16,432} = 1.85, P = 0.02, \eta^2_p = 0.0642$; Figure 2-3A). Post-hoc analyses revealed that the mixed action displayed greater ankle inversion at FIC compared to the semi-open action. For the front-foot lower limb angles, no significant effect was observed for the main effect of action type ($F_{2,54} = 1.12, P = 0.33, \eta^2_p = 0.0397$) or the three-way joint angle interaction for stages*angles*actions ($F_{64,1728} = 1.13, P = 0.23, \eta^2_p = 0.04$; Figure 2-3B). No significant main effect of action type was observed for torso joint angles from BIC to AV ($F_{2,54} = 1.01, P = 0.37, \eta^2_p = 0.0362$). A significant three-way stages*angles*actions interaction was seen for the torso joint angles across the BIC to AV stages ($F_{50,1350} = 1.4, P = 0.03, \eta^2_p = 0.0495$; Figure 2-4A), with post-hoc analyses finding a significantly higher T12-L1 left rotation at BIC for mixed compared to semi-open. The upper-bowling arm joint angles showed no significant main effect of action type ($F_{2,54} = 1.6, P = 0.21, \eta^2_p = 0.0555$) but a significant three-way interaction for stages*angles*actions ($F_{30,60} = 1.8, P < 0.05, \eta^2_p = 0.0624$; Figure 2-4B). Post-hoc analyses saw front-on bowlers display significantly less elbow pronation at BIC compared to mixed and semi-open, whereas the semi-open action displayed significantly less elbow pronation compared to the mixed action at FIC and FV.
Figure 2-3  Mean (± SE) values of nine lower limb joint angles at back-foot contact phase (BIC, A), and front-foot contact phase (FIC, B) across bowling action types and stages of the bowling action. The following rotations are positive: ankle dorsiflexion, forefoot adduction, ankle inversion, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction and hip internal rotation.
Figure 2-4  Mean (± SE) values of six torso joint angles (A) and seven bowling arm joint angles (B) across bowling action types and stages of the bowling action. The following rotations are positive: L5-S1 flexion, L5-S1 left lateral flexion, L5-S1 right rotation, T12-L1 flexion, T12-L1 left lateral flexion, T12-L1 right rotation, shoulder forward flexion, shoulder adduction, shoulder internal rotation, elbow flexion, elbow pronation, wrist flexion and ulnar deviation.
2.4.3 Segment Alignment Angles

The results for segment alignment angles showed a significant main effect of action type \( (F_{2,54} = 33.15, P < 0.05, \eta^2_p = 0.5511) \) and a significant two-way interaction for angles*actions \( (F_{20,540} = 7.52, P < 0.05, \eta^2_p = 0.2179; \text{Figure 2-5}) \). When post-hoc analyses were performed, a number of significant findings were observed. There was significantly more shoulder counter-rotation in the mixed action compared to the front-on and semi-open actions. A significant reduction in shoulder alignment at BIC was found for the semi-open action compared to the front-on and mixed actions. A significantly higher peak shoulder alignment was observed in the front-on action compared to the semi-open action. Finally, the shoulder-pelvis separation angle at BIC was significantly greater for mixed compared to semi-open action.

![Figure 2-5](image_url)

**Figure 2-5** Mean (± SE) segment alignment angles across bowling action types. BIC (back-foot initial contact), FIC (front-foot initial contact), SH (shoulder), SEP (separation), ALIGN (alignment), MAX (maximum).
2.4.4 Torso Joint Range of Motion

No significant main effect of action type was observed torso ROM between BIC and FIC ($F_{2,54} = 3.13$, $P = 0.052$, $\eta^2_p = 0.1039$). A significant ROM*actions interaction was observed for the BIC to FIC stages comparison for the torso region ($F_{10,270} = 3.48$, $P < 0.05$, $\eta^2_p = 0.1141$; Figure 2-6A), with post-hoc analyses finding a significant increase in T12-L1 left/right rotational ROM in the mixed action compared to front-on and semi-open actions. However, the FIC to BR comparison showed no significant no main effect of action type ($F_{2,54} = 0.69$, $P = 0.51$, $\eta^2_p = 0.0247$) nor a significant interaction of ROM*actions in the torso region ($F_{10,270} = 1.47$, $P = 0.15$, $\eta^2_p = 0.0517$; Figure 2-6B).
Figure 2-6  Mean (± SE) values of L5-S1 and T12-L1 joint range of motion (ROM) during back-foot contact phase (A) and front-foot contact phase (B) across action types.
2.4.5 Trunk-Pelvis Angle and Segment Angles

Analysis of the trunk-pelvis angles, pelvis segment angles and trunk angles showed a significant main effect of action types ($F_{2,54} = 3.87$, $P = 0.03$, $\eta_p^2 = 0.1252$) and a significant interaction for stages*angles*actions ($F_{80,2160} = 2.09$, $P < 0.05$, $\eta_p^2 = 0.0718$; Figure 2-7). Post-hoc analyses showed a significantly lower trunk-pelvis right rotation angle at BIC in the semi-open action compared to the mixed bowling actions. Post-hoc analyses showed a significantly higher trunk left rotation at BIC in the semi-open action compared to the front-on and mixed actions. There was also significantly less trunk left rotation at BR in the semi-open and mixed actions compared to front-on action, while there was significantly greater trunk right rotation at AV in the front-on action compared to semi-open and mixed actions.

![Graph showing mean (± SE) values of trunk-pelvis angles, pelvis segment angles and trunk segment angles across bowling action types and stages of the bowling action. The following rotations are positive: trunk-pelvis extension, trunk-pelvis right flexion and trunk-pelvis right rotation, pelvis extension, pelvis right flexion and pelvis left rotation, trunk extension, trunk right flexion and trunk right rotation.](image.png)

Figure 2-7 Mean (± SE) values of trunk-pelvis angles, pelvis segment angles and trunk segment angles across bowling action types and stages of the bowling action. The following rotations are positive: trunk-pelvis extension, trunk-pelvis right flexion and trunk-pelvis right rotation, pelvis extension, pelvis right flexion and pelvis left rotation, trunk extension, trunk right flexion and trunk right rotation.
2.4.6 Ground Reaction Force

For the GRF data, a significant main effect of action types was observed ($F_{2,53} = 4.21$, $P = 0.02$, $\eta^2 = 0.1372$) and a significant interaction of force*actions interaction was observed ($F_{14,371} = 4.22; P > 0.05$, $\eta^2 = 0.1373$; Figure 2-8A), with post-hoc analyses showing a significantly lower loading rate (LRF) for semi-open action compared to front-on and mixed actions during front-foot contact phase. No significant main effect of action types on impulses were observed ($F_{2,53} = 0.74$, $P = 0.48$, $\eta^2 = 0.0272$) nor a significant interactions were found for impulse*actions ($F_{8,212} = 0.84; P = 0.57$, $\eta^2 = 0.0308$; Figure 2-8B). For the time to peak GRFs, no significant main effect was observed for action types ($F_{2,53} = 2.05$, $P = 0.14$, $\eta^2 = 0.0717$) nor a significant interaction of timing*actions ($F_{14,371} = 0.89; P = 0.57$, $\eta^2 = 0.0324$; Figure 2-8C).
Figure 2-8  Mean (± SE) values of peak GRF (relative BW) and FV loading rate (BW·s⁻¹) (A), impulse (relative BW) (B), and timing of peak GRF (s) (C) across bowling action types.
2.4.7 Joint Moments and Forces

No significant main effect of action types was observed for front lower-limb joint moments ($F_{2,50} = 0.61, P = 0.55, \eta^2_p = 0.0237$). There were also no significant interaction of moments*actions for front lower-limb joint moments ($F_{34,850} = 0.81, P = 0.77, \eta^2_p = 0.0316$; Figure 2.9A). Similarly, torso joint moments saw no significant main effect for actions types ($F_{2,49} = 0.32, P = 0.73, \eta^2_p = 0.013$) and no significant interaction of moments*actions ($F_{22,539} = 1.12, P = 0.32, \eta^2_p = 0.0437$; Figure 2.9B). For the L5-S1 and T12-L1 joint forces, no significant main effect of action type was observed ($F_{2,53} = 1.73, P = 0.19, \eta^2_p = 0.0612$) nor any significant interaction for joint force*actions ($F_{12,318} = 1.4; P = 0.16, \eta^2_p = 0.0502$; Figure 2.9C).
Figure 2-9  Mean (± SE) values of peak front lower limb (A), torso joint (B) moments (relative BM x height) and joint forces (C) (relative to BM) across bowling action types.
2.5 Discussion

Through the use of a standard bowling action classification system (Ferdinands et al., 2014), this study is the first to provide a comprehensive comparison of the 3D kinematic and kinetic variables associated with different types of fast bowling action in junior athletes. Such a comparison is necessary to investigate if differences in 3D kinematic and kinetics characteristics in this multi-planar movement exist between action types and could potentially effect performance (e.g. ball speed) and/or lumbar spine injury risk. This study resulted in a number of significant findings between the major action types that will be explored within this discussion.

As expected, significant differences in action types were observed for shoulder counter-rotation as this variable was utilised to define the action types. Significantly greater shoulder counter-rotation was observed here in the mixed action (49 ± 1°) compared to the non-mixed bowling actions (front-on 35 ± 2°; semi-open 28 ± 2°). Closer examination of the mixed action found that shoulder counter-rotation was distributed mostly between 40-50° (61%), followed by 50-60° (27%) and 60°+ (12%). It is unknown if a threshold of shoulder counter-rotation exists in which bowling performance and/or increased lumbar spine injury risk are significantly altered.

Shoulder-pelvis separation angle was found to be significantly different between fast bowling action types. Increased shoulder-pelvis separation angle at BIC of the mixed action (26°) compared to semi-open action (10°) was seen within this current study. This may place the lower back under stress from the start of the action, as increased separation angle has been related to soft tissue injury (Portus et al., 2004). As back-foot contact phase kinetics were not collected within this current study, we are unable to comment on any effects on lumbar loading that might result from increased separation angle during this phase. It also does not appear that shoulder-pelvis separation angle during this bowling action has an influence on ball speed with no significant differences in ball speed observed between action types in this current study.
The movement of the lumbar spine is of particular importance when performing the fast bowling action. Mixed action bowlers in this study displayed greater T12-L1 joint ROM (36 ± 3°) compared to front-on (27 ± 4°) and semi-open bowlers (25 ± 3°) during the back-foot contact phase (See Figure 2B). These differences in torso motion are likely related to the excessive amount of trunk rotation of the mixed action compared to the non-mixed actions, leading to greater movement at the T12-L1 joint in this mixed action. Without the aid of torso joint kinetics during the back-foot contact phase, due to only having two 400 x 600 mm force platforms that could only measure kinetics during front-foot contact phase, it is unclear whether high levels of T12-L1 ROM are influential on lumbar spine loading in mixed bowling actions compared to other actions.

In addition, the trunk segment angles at BIC differed between the fast bowling action types. This current study observed at BIC, the trunk segment in the semi-open action was in a more left-rotated position away from the bowling arm (-50 ± 2°) than both the front-on (-31 ± 3°) and mixed actions (-27 ± 2°). This trunk position in the semi-open action is likely due to the shoulders being in a more left-rotated alignment at the point of back-foot initial contact. Again, the lack of torso kinetics during this period does not allow for this current research to elaborate any influences on lumbar loading.

The action types differing in their spinal kinematics during back-foot contact may translate to differences in rear-leg kinematics and kinetics during the delivery stride. Previous research has shown that rear thigh velocity makes a significant contribution to rear-leg drive and bowling wrist speed (Greene et al., 2014). This current study found increased ankle inversion in mixed bowlers (8 ± 2°) compared to semi-open bowlers (3 ± 2°). It is unclear whether this ankle movement observed in this current study may contribute to greater rear-leg push-off from back-foot to front-foot contact for mixed bowlers.
Unlike rear-leg kinematics, the front-leg kinematics of the fast bowling action have been investigated. Increased knee extension has been related to increased ball speed and also to greater injury risk, but no effect of bowling action type on front-leg kinematics has been reported (Olivier et al., 2015; Portus et al., 2004; Worthington et al., 2013a). No differences in this current study in front-leg joint angles across action types were seen here, suggesting that junior fast bowlers adopt similar front-leg kinematic strategies despite employing different trunk mechanics according to their fast bowling action type.

Bowling arm differences between action types are not yet known, only delayed shoulder circumduction has been related to increased ball speed (Worthington et al., 2013b). Differences in elbow pronation were observed here between the action types, specifically at BIC for front-on action (79.2°) compared to mixed action (115.3°) and semi-open and semi-open (111.1°), at FIC for mixed action (85.3°) and semi-open action (49.5°), and again at FV for mixed and semi-open actions (75.4° & 43.9°, respectively). The between-group differences in elbow pronation are possibly related to pre-release strategies positioning the ball for performance outcomes such as increased in- or out-swing.

It is known that the fast bowling action is a highly stressful movement placing high loads on the body (Crewe et al., 2013; Worthington et al., 2013a). The only difference between action types observed in the kinetic data in junior bowlers within this study was a decreased loading rate of the vertical GRF for semi-open bowlers (285 ± 27BW·s⁻¹) compared to both front-on (399 ± 30BW·s⁻¹) and mixed bowlers (357 ± 22BW·s⁻¹). However, this does not appear to impact the injury risk of front-on and mixed bowlers as no significant differences in peak GRFs (Figure 2-8A) or L5-S1 or T12-L1 joint loading (Figure 2-9B-C) were seen. This may suggest, once bowlers begin the front-foot contact phase, load is transferred along the kinetic chain at different rates in all three action types.
While GRFs have been reported during back-foot contact in adult bowlers (Hurrion et al., 2000; Portus et al., 2004), no research has elaborated on back-foot contact phase lumbar loading in neither junior nor adult bowlers. Therefore, as the majority of differences in action type, particularly involving the trunk and lumbar region, occur during the back-foot contact phase of the bowling action, a shift of focus away from front-foot lumbar loading may be indicated. Instead, exploration of back-foot lumbar loading between action types may be required to determine if the action classification parameters are a true reflection of injury risk, and whether it correlates to bowling performance.

A limitation of this study was that although every attempt was made to recreate match-like conditions, the participants were unfamiliar with the laboratory environment and this possibly affected their bowling performance. However, the conditions were the same for all three bowling action groups. The type of pitch surface was different between cohorts and thus laboratories, with a 20 mm athletic track for cohort 1 (n = 20) and cohort 2 (n = 17) and a concrete surface for cohort 3 (n = 23) participants. There were only enough force platforms available to measure kinetics during the front-foot contact phase, therefore this study was unable to provide analysis of kinetics during back-foot contact phase. Although the sample size of this cohort was relatively large, the small size of the side-on action group led to this group being excluded from analysis, leaving a gap in the research regarding this action type.

2.6 Conclusion
Fast bowlers adopt a particular action type in order to generate high ball velocities. This study has provided an in-depth exploratory 3D comparison of the fast bowling actions, with the mixed action demonstrating higher lumbar motion and shoulder-pelvis separation angles during the back-foot contact phase than the other actions. Thus, analysis of lumbar region kinetics during back-foot contact phase is warranted to establish whether differences in kinematics during this phase results in changes lumbar loading and/or bowling performance. Yet, during the front-foot contact phase
no significant differences in loading nor bowling performance were observed between action types suggesting that fast bowlers attenuate forces at similar rates during this phase in spite of their action type differences and attain similar ball speeds. Further research is also needed on side-on fast bowlers to determine if there are significant differences in this action compared to those presented here.

2.7 Acknowledgements
The authors of this study acknowledge Professor Robert Robergs for his assistance with the LabView software to analyse ground reaction force data. The authors also acknowledge Cricket NSW for assistance with recruiting participants for one of the participant cohorts. Funding for the testing of one of the participant cohorts was provided by an iCare sports injury grant.

**INFORMATION BOX**

**What is already known on this topic?**
- Fast bowling is a highly complex movement with the aim to produce as high ball velocity as possible.
- Fast bowlers are typically categorised into four major action types: side-on, front-on, semi-open and mixed.

**What this study adds?**
- Provides a comprehensive 3D kinematic and kinetic comparison of the front-on, semi-open and mixed fast bowling actions.
- The semi-open bowling action generates a lower loading rate compared to both the front-on and mixed bowling actions but similar ball speed is observed across all action styles.
2.8 References


Context of Manuscript in Relation to the Thesis

Fast bowling can result in high levels of low back injury in junior and adult fast bowlers, typically leading to increased loss of match time in these injured bowlers. This is a hindrance to the fast bowling athlete as a loss of match time can limit bowling performance. Since fast bowling is a high loading and complex multi-faceted movement, the bowling technique is considered a risk factor for increased lumbar spine injury. Manuscript 1 investigated the differences between action types in junior fast bowlers, whereas Manuscript 2 provides an exploration into the relationship between bowling technique and lumbar spine injury in these junior athletes. It is known that lumbar spine abnormalities such as bone oedema are a precursor to conditions such as stress fractures of the lumbar vertebrae in junior fast bowlers. The following manuscript fits with the overall scope of the thesis by investigating which biomechanical variables of the fast bowling action can be linked to lumbar spine injury in junior fast bowlers.
Chapter 3     Biomechanical links between lumbar spine abnormality and junior fast bowling technique

This chapter is an amended version of the manuscript: Schaefer, A., Ferdinands, R.E.D., O’ Dwyer, N., & Edwards, S. Kinematic links between lumbar spine injury and junior fast bowlers. To be submitted to the British Journal of Sports Medicine.

3.1 Abstract
Background: Fast bowling is a high-impact activity, leading to a high incidence of lumbar injury, particularly in junior fast bowlers. Abnormalities of the lumbar spine such as bone oedema are known to predict stress fractures by the end of a season in junior fast bowlers. Previous research has linked the mixed bowling action, shoulder counter-rotation, front-knee extension and trunk lateral flexion to increased incidence of lumbar injury in adult fast bowlers.

Aim: The study’s purpose was to investigate biomechanical risk factors during junior fast bowling related to lumbar spine abnormalities (LSAs).

Methods: Three-dimensional (3D) kinematic, kinetic and MRI data were collected from nine male junior fast bowlers with a LSA and 11 without a LSA during a five-over spell at match pace. Kinematic and kinetic data were collected for rear-leg, front-leg, trunk and bowling arm during the bowling action. Mixed-design factorial analyses of variance were used to determine between-group differences. Magnetic resonance imaging (MRI) was conducted to determine if a LSA was present in each participant.

Results: MRI analysis found that of the nine bowlers with a LSA, six had a mixed action, two displayed a semi-open action and one had a front-on action. No significant between-group differences were observed in this study for shoulder counter-rotation or lumbar spine loading. Significantly greater knee extension at ball-release, hip
internal rotation at arm-horizontal and reduced thoraco-lumbar range of motion were seen in the front limb for participants with LSA compared to their counterparts without LSA.

**Conclusions:** In this study, LSAs were linked with the mixed bowling action, but also observed in bowlers with the semi-open and front-on actions. A link could not be established between those with a LSA and those without LSA with traditionally accepted bowling injury mechanisms such as shoulder counter-rotation and trunk lateral flexion during fast bowling in this study. Rather, the motion of the front lower limb may play a role in transferring load to the lumbar spine, as those with a LSA utilised a straighter front limb, potentially affecting injury risk. During back-foot contact phase, restricted thoraco-lumbar rotation in those with an LSA may be linked to lumbar spine injury through an inability to dissipate load.

### 3.2 Introduction

The fast bowling action is a complex high-loading activity resulting in a high incidence of lumbar spine injuries (Stretch, 2003). Such injuries in bowling are predominantly overuse injuries, such as spondylolysis, spondylolisthesis, pedicle sclerosis and intervertebral disc degeneration, leading to stress fractures and spinal disc degeneration (Portus et al., 2004; Glazier, 2010; Elliott et al., 1992; Foster et al., 1989). The injury incidence can be as high as 53% among senior players and 24% in junior players (Stretch, 2003; Elliott and Khangure, 2002). Recent investigation has also identified that lumbar spine abnormalities (LSAs), such as bone oedema are linked to stress fractures in the lumbar vertebrae in junior fast bowlers (Kountouris et al., 2012). Asymptomatic fast bowlers that display lumbar bone oedema in a season are between 70-100% more likely to incur a stress fracture to the lumbar vertebrae in the following season (Kountouris et al., 2012, 2013; Ranson et al., 2008). Though previous research has linked these high injury incidences to fast bowling technique (Portus et al., 2004; Foster et al., 1989; Stuelcken et al., 2010), it is unclear if the same mechanisms influence the development of LSAs.
Fast bowling actions are classified into four broad categories: side-on, front-on, semi-open and mixed (Ferdinands et al., 2010a), of which the mixed action has been linked with an increased incidence of lumbar spine injury (Portus et al., 2004). The mixed action is characterised by greater shoulder counter-rotation (30°−40°) than the other action types (Bartlett et al., 1996; Elliott, 2000). An increase in shoulder counter-rotation has previously been linked to both increased lumbo-pelvic loading and lumbar spine injury risk in junior fast bowlers (Portus et al., 2004; Foster et al., 1989; Elliott and Khangure, 2002; Crewe et al., 2013; Ferdinands et al., 2010b). Shoulder counter-rotation alone may not be responsible for lumbar spine injury, however, as other risk factors also have been identified.

The knee joint of the front limb which is second lower limb to contact the ground during the bowling action (‘front’ limb) plays an important role in the attenuation of the force of the foot-ground contact during fast bowling. High levels of vertical and horizontal ground reaction force (GRF) have been measured during front foot contact in junior fast bowlers: 2.7-7.2 x body weight (BW) and 1.6-5.2 BW, respectively (Crewe et al., 2013). Front knee mechanics may influence the transmission of GRFs to the lumbar spine. For instance, a front knee that flexes during front foot contact should ‘cushion’ the impact, just as when the knees flex to during the landing phase of a jump-landing task (Norcross et al., 2013). Such a load reduction mechanism may explain why a more flexed knee at a front foot flat position may reduce lumbo-pelvic loading and lumbar spine injury risk (Ferdinands et al., 2010b; Olivier et al., 2015). In terms of fast bowling performance, however, a more extended front knee at contact has been associated with increased ball speed in adult fast bowlers (Portus et al., 2004; Worthington et al., 2013a). Therefore, more analysis is required to determine how influential the front knee mechanics is associated with lumbar spine injury risk.

It is likely that lumbar spine injuries are influenced by the interconnecting segments of the trunk (thoracic, lumbar) and the pelvis. Increased thoracic and pelvic rotation at ball-release appears to result in greater rotational forces and moments of the
lumbo-pelvic region, occurring when the vertical GRF is the highest in junior and adult fast bowlers (Ferdinands et al., 2010b; Ferdinands et al., 2009). Greater lateral trunk flexion away from the bowling arm and shoulder-pelvis separation angle also have been related to lower back pain and lumbar spine injury in adult fast bowlers (Portus et al., 2004; Stuelcken et al., 2010). However, little evidence exists to determine the amount of trunk and pelvis rotation, lateral trunk flexion or shoulder pelvis separation during the fast bowling action that would increase the risk of lumbar spine injury.

With limited research available on the risk factors associated with lumbar spine injury during fast bowling, the purpose of this study was to identify the biomechanical factors associated with lumbar spine abnormalities (LSAs) in a sample of junior fast bowlers. The researchers hypothesised that junior fast bowlers with LSAs would demonstrate greater shoulder counter-rotation, shoulder-pelvis separation angle, trunk lateral flexion, front knee extension and lumbar loading than those without an LSA.

3.3 Methods

3.3.1 Participants

Twenty junior male fast bowlers aged between 13 and 16 years were recruited from local district and zone (pre-state) level representative teams within regional New South Wales (mean age: 13.9 ± 0.9 yr, height: 1.75 ± 0.08 m, mass: 61.6 ± 9.6 kg). Participants were classified as fast bowlers by the director of coaching of their corresponding districts. At the time of testing participants were cleared of back pain by a physiotherapist. Written informed consent was obtained prior to data collection from the participants and their parent/guardians, with all methods approved by the institution’s Human Research Ethics Committee (2014/169; H-2015-0059).

3.3.2 Experimental Protocol

Prior to preparing the participant for a static standing trial, height, body mass, and trunk and pelvic dimensions were measured. Next, the participants completed
standardised warm-up exercises (Bird and Stuart, 2012), followed by six practice deliveries to familiarise them to the laboratory environment. A five-over spell (5 x 6 deliveries) of bowling was then conducted that took ~1 hour to complete. The spell consisted of bowling at match pace (self-paced and self-selected run-up distance) on a standard cricket pitch (20.12 m), with the participants attempting to land the ball on the pitch 6-8 m from the batsmen’s end. There was a non-bowling period between each over to simulate game conditions, the protocol for which has been reported previously in Schaefer et al. (2018).

Three-dimensional (3D) kinematic and kinetic data were recorded for every delivery (30 deliveries) in the five-over spell. Whole body 3D motion of the participant was recorded (500 Hz) with a 16-camera motion capture system (Oqus 700+, Qualisys AB, Göteborg, Sweden). Passive reflective markers were placed on the lower and upper limbs, pelvis, torso and head (Figure 3-1) which included makers on the lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, the ribcage bilaterally at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker and the lumbar segment (five tracking markers) following the protocol of Schaefer et al. (2018) and Crewe et al. (2013). To minimise marker occlusion, the participants wore minimal clothing of shorts, socks and athletic shoes. All 3D GRFs were measured (2,000 Hz) using two multichannel force platforms (Type 9281CA and 9281EA, Kistler, Winterthur, Switzerland) embedded in the floor and connected to a control unit (Type 5606, Kistler, Winterthur, Switzerland).
Figure 3-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. Static markers were used for the static trial and removed for dynamic trials (including L-R 1st metatarsal, L-R medial malleolus, L-R medial femoral epicondyle) (Schaefer et al., 2018, p.10).

3.3.3 Data Reduction

The kinematic and kinetic data for all 30 deliveries were analysed using Visual3D software (Version 5, C-Motion, Germantown, MD). All data, including raw kinematic, GRF, moment and centre of pressure data, were low-pass filtered (Butterworth digital, fourth-order zero-phase with $f_c = 18$ Hz). The filtered data were then used to calculate the individual joint kinematics, and the net internal joint moments and forces during front foot-ground contact (Bisseling and Hof, 2006). The temporal stages of the front foot-ground contact during the bowling action were defined and confirmed by visual inspection. Temporal stages included back-foot initial foot-ground contact (BIC), front-foot initial ground contact (FIC), peak vertical ground reaction force (FV), bowling upper-arm horizontal backwards (AH), ball release (BR), and bowling upper-arm vertically downwards (AV) according to Schaefer et al. (2018) (Figure 3-2). The back-foot contact phase is defined from BIC to FIC, whereas the front-foot contact phase is defined from FIC to AV. The definitions of the segmental angles included pelvis
alignment, pelvis counter-rotation, shoulder alignment, shoulder counter-rotation and shoulder-pelvis separation angle, based on the protocol of Ferdinands et al. (2010a).

Figure 3-2  Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer et al., 2017, p.3)

Peak magnitudes and loading rates of GRFs were calculated using raw GRF data that was low-pass filtered at 50 Hz (Butterworth digital, 4th-order zero-phase) using a customised program (LabView, National Instruments Corporation, Austin, USA). Segment masses and inertial properties, and the Cartesian local coordinate system and sequence of rotation were defined according to Schaefer et al. (2018). Ranges of motion (ROM) for L5-S1 (5th lumbar - 1st sacral vertebrae) and T12-L1 (12th thoracic - 1st lumbar vertebrae) joints between BIC-FIC and FIC-BR were calculated as the difference between the peak maximum and minimum joint angles during each period.

3.3.4 Data Analysis

Inverse dynamics were used to estimate net internal joint forces and moments and peak GRF variables during the front-foot contact phase. When the participant’s front-foot did not wholly contact the force platforms during the front-foot contact phase, the corresponding kinetic data were excluded from statistical analysis (unsuccessful trials = 25.8 ± 16.1%). Peak net internal joint moments were normalised to body mass multiplied by height (relative BM x height), and L5-S1 and T12-L1 joint forces were normalised to body weight (relative BW). As researchers often use the incorrect assumption that GRF variables infer joint loading, both GRF and joint loading variables were included within this analysis (Edwards et al., 2014).
The fast bowling action classification parameters were implemented from the protocol of Ferdinands et al. (2014) to classify each participant’s action as either side-on, front-on, semi-open or mixed action. Although the original protocol further divided the mixed bowling into 15 sub-categories, we analysed the sample data only in relation to these four basic action types.

3.3.5 Magnetic Resonance Imaging (MRI)

All participants underwent an MRI scan of the lumbar spine at the beginning of the season to assess the presence of LSAs as a baseline. The MRI scans were performed by a single radiology company using GE Signa 1.5T (HDe, HDx & 360) machines (GE Medical Systems, Milwaukee, Wisconsin). A phased-array spinal coil was used to collect sagittal and axial images to optimise visualisation of the individual pars of the 1st to 5th lumbar vertebrae (L1 to L5). The sagittal T2- and T1-weighted and short tau inversion recovery (STIR) sequences were performed at a field of view (FOV) 28cm, 4mm slice thickness and 0.5mm spacing (TR 3480ms, TE 102ms, ETL21, 480 x 256 matrix, NEX 3 for T2 FRFSE weighting; TR 655ms, TE minimum full, ETL 2, 352 x 224 matrix, NEX 2 for T1 FSE weighting; TR 3525ms, TE 45ms, TI 145ms, 288 x 192 matrix, NEX 3 for STIR weighting).

Axial sequences consisted of T2-weighted imaging from the inferior end-plates of L3 to S1 at FOV 20cm, 4mm slice thickness and 0.5 mm spacing (TR 5420ms, TE 90ms, ETL 19, 352 x 224 matrix, NEX 3, Phase FOV 0.8 for T2 FRFSE weighting). An axial sequence was also performed at higher levels where the stress related signal was identified. The coronal imaging consisted of T1-weighted fat saturated (FS) 3D to visualise the whole vertebral column from L1 to S2. The 3D SPoiled GRASS (SPGR) CHEmical Shift Selective Pulses (CHESS) FS sequences were performed at FOV 32cm, 2mm slice thickness 60 locs to the slab (Flip angle 12, TE In Phase, 256 x 192 matrix, NEX 2, Phase FOV 0.7). These were then reconstructed in all three cardinal planes as well as the sagittal oblique plane to view the cortical bone of the pars. Coronal STIR sequences were also performed to visualise the pars of the vertebrae and sacroiliac joints at FOV 29cm, 4mm slice thickness and 0.5mm spacing (STIR weighting TR 4775ms, TE 45ms, TI 145ms,
Chapter 3: Manuscript 2

288x192 matrix, 3 NEX). Each scan was assessed independently by a single experienced radiologist, with the conditions of the pars interarticularis and discs graded according to the classification system of Hollenberg et al. (2002).

3.3.6 Statistical Analysis

The means and standard deviations for all variables were calculated for all deliveries of the spell. A series of mixed-design factorial analyses of variance (ANOVAs) were employed to determine significant changes (P < 0.05) in outcome variables between groups of bowlers without (non-injured) and with LSA. For simplicity, we split the outcome variables into the following categories for the primary test of the effect of LSA: angles, alignments, trunk-pelvis angles, and trunk and pelvis segment angles, ranges of motion (ROMs), joint velocities, GRFs, joint moments and joint forces.

The primary test of the effect of LSA was then conducted into the following factors for the outcome variables. There were three factors for analyses of joint angles (stages*angles*LSA), trunk-pelvis angles (stages*angles*LSA) and trunk/pelvis segment angles (stages*angles*LSA). The stages encompassed the six critical time points of the bowling action (BIC, FIC, FV, AH, BR, AV), while the angles incorporated the 22 joint angles, three trunk-pelvis angles, three trunk segment angles and three pelvis segment angles. There were two factors for the analyses of alignment angles (align*LSA), joint velocities (velocity*LSA), velocity timings (timing*LSA), joint ROMs (ROM*LSA), all GRF variables (force*LSA, impulse*LSA, timing*LSA), joint moments (moment*LSA) and joint forces (jtforce*LSA). There was one group factor (LSA present or absent) in these analyses, while all others were repeated measures factors. Since the primary interest of the study was the effect of LSA, only main effects and interactions involving the LSA factor will be reported in the results. Partial eta squared were included to estimate effect sizes for all interactions of the ANOVAs. Effects sizes (η_p^2) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson, 2011).
All ANOVAs were calculated using Statistica (v.13, StatSoft Inc., Tulsa, OK, USA), with Tukey post hoc tests selected to identify which outcome variable produced the significant effect. All data were examined to satisfy the assumptions of normality of distribution and sphericity, with multivariate ANOVA used when sphericity was not satisfied. Assumptions of constant variance and normality were examined through residuals and were both satisfied and accepted. If Tukey post hoc did not indicate a significant effect following a significant interaction of ANOVAs, univariate and independent t-tests were employed to assess which variable was responsible for the interaction and effect size analyses, respectively.

3.4 Results

3.4.1 Action Classification and Injury Status

The proportions of action types in the bowling sample were side-on \( n = 1 \) (5%), front-on \( n = 5 \) (25%), semi-open \( n = 4 \) (20%) and mixed \( n = 10 \) (50%). The incidence of lumbar spine abnormalities varied across action types, being highest in the mixed action (Table 3-1).

<table>
<thead>
<tr>
<th>Action type</th>
<th>Non-injured (n=11)</th>
<th>LSA (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-on</td>
<td>1 (9%)</td>
<td>0</td>
</tr>
<tr>
<td>Front-on</td>
<td>4 (36%)</td>
<td>1 (11%)</td>
</tr>
<tr>
<td>Semi-open</td>
<td>2 (18%)</td>
<td>2 (22%)</td>
</tr>
<tr>
<td>Mixed</td>
<td>4 (36%)</td>
<td>6 (67%)</td>
</tr>
</tbody>
</table>

3.4.2 Joint and Alignment Angles

Alignment angles showed no main effect of LSA (\( F_{1,18} = 0.001, P = 0.97, \eta^2_p = 0.0001 \)) nor any significant interaction for align*LSA (\( F_{11,198} = 0.82, P = 0.62, \eta^2_p = 0.0435 \); Figure 3-3). There was no main effect of LSA for the front-foot lower limb angles (\( F_{1,18} = 0.25, P = 0.62, \eta^2_p = 0.0137 \) but post-hoc analyses of a significant interaction of
Chapter 3: Manuscript 2

angles*stages*LSA ($F_{32,576} = 2.13$, $P > 0.05$, $\eta^2_p = 0.1059$) showed significantly greater hip internal rotation at AH compared to external rotation in the non-injured group, and also decreased knee flexion at BR in the LSA group than the non-injured group (Figure 3-4A). The results for torso angles indicated no significant main effect for LSA ($F_{1,18} = 0.8$, $P = 0.38$, $\eta^2_p = 0.0424$). While a significant interaction for angles*stages*LSA ($F_{25,450} = 1.84$, $P = 0.008$, $\eta^2_p = 0.0929$) was observed, post-hoc analyses indicated no significant between-group differences for any L5-S1 or T12-L1 joint angles (Figure 3-4B). The univariate results indicated a significant effect of T12-L1 rotation at FIC ($P = 0.007$), with greater left T12-L1 rotation in the non-injured group ($21 \pm 2^\circ$) compared to the LSA group ($11 \pm 2^\circ$; $d = 1.45$). For trunk-pelvis joint angles, pelvis segment angles and trunk segment angles, there was no significant main effect of LSA ($F_{1,18} = 0.39$, $P = 0.54$, $\eta^2_p = 0.0212$) or interaction for angles*stages*LSA ($F_{40,720} = 1.34$, $P = 0.08$, $\eta^2_p = 0.0692$; Figure 3-4C). The results for the rear-leg and bowling arm angles are shown in Appendix 7.9 (Figure 7-2).

![Figure 3-3](image_url)  
**Figure 3-3** Mean ± standard error (SE) of segment alignment angles for non-injured and LSA groups.
Figure 3-4  Mean (± SE) values of nine lower limb joint angles for front-foot contact phase (A), six torso joint angles (B) and trunk-pelvis angles, and pelvis and trunk segment angles (C) across stages of the bowling action for non-injured (Non-Inj) and LSA groups. The following rotations are positive: ankle dorsiflexion, inversion, forefoot adduction, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction, hip internal rotation, L5-S1 flexion, L5-S1 left lateral flexion, L5-S1 left rotation, T12-L1 flexion, T12-L1 left lateral flexion, T12-L1 left rotation, trunk-pelvis extension, trunk-pelvis right flexion and trunk-pelvis left rotation, pelvis extension, pelvis right flexion and pelvis left rotation, trunk extension, trunk right flexion and trunk left rotation. N.B. * denotes significant results.
3.4.3 Joint Range of Motion

No significant main effect of LSA resulted for torso ROM between BIC to FIC \((F_{1,18} = 1.13, P = 0.3, \eta^2_g = 0.0589)\). Post-hoc analysis of the significant ROM*LSA interaction \((F_{5,90} = 2.96, P = 0.02, \eta^2_g = 0.1411)\) showed a significantly lower T12-L1 rotational ROM between BIC to FIC in bowlers with LSA compared to the non-injured bowlers (Figure 3-5A). The results for torso joints ROM between FIC and BR showed no significant main effect of LSA \((F_{1,18} = 0.38, P = 0.54, \eta^2_g = 0.0209)\) nor ROM*LSA interaction \((F_{5,90} = 2.17, P = 0.06, \eta^2_g = 0.1076, \text{Figure } 3-5B)\).

\[\text{Figure 3-5} \quad \text{Mean (± SE) values of L5-S1 and T12-L1 joint ROM from BIC to FIC (A) and FIC to BR (B) across non-injured and LSA groups. * denotes significant results.}\]

77
3.4.4 Joint Velocity Peaks and Timing

For L5-S1 and T12-L1 peak joint velocities across the four phases of the bowling action, no main effect was seen for LSA ($F_{1,18} = 0.18, P = 0.29, \eta_p^2 = 0.0617$). There was a significant interaction for velocity*LSA ($F_{42,756} = 1.47, P = 0.03, \eta_p^2 = 0.0756$) but post-hoc analyses found no significant between-group effects (Figure 3-6A). Time to peak torso joint velocity revealed no main effect of LSA ($F_{1,18} = 0.78, P = 0.39, \eta_p^2 = 0.0416$), nor was there a significant interaction for timing*LSA ($F_{5,90} = 0.81, P = 0.54, \eta_p^2 = 0.0433$; Figure 3-6B).

3.4.5 Ground Reaction Forces and Loading Rate

There was no main effect of LSA during the front-foot contact phase for peak GRF variables and loading rate ($F_{1,18} = 0.59, P = 0.45, \eta_p^2 = 0.0316$), impulse ($F_{1,18} = 0.23, P = 0.64, \eta_p^2 = 0.0124$) or timing variables for LSA ($F_{1,18} = 0.32, P = 0.58, \eta_p^2 = 0.0174$), nor their respective interactions of force*LSA ($F_{7,126} = 0.58, P = 0.77, \eta_p^2 = 0.0312$; Figure 3-7A), impulse*LSA ($F_{4,72} = 0.52, P = 0.72, \eta_p^2 = 0.0283$; Figure 3-7B) and timing*LSA ($F_{7,126} = 0.91, P = 0.5, \eta_p^2 = 0.0484$; Figure 3-7C).
Figure 3-6  Mean (± SE) values of peak torso joint velocity (A), and time to peak torso joint velocity (B) across non-injured and LSA groups.
Figure 3-7  Mean (± SE) values of peak GRF (relative BW) and $F_{VT}$ loading rate (BW·s$^{-1}$) (A), impulse (BW·s) (B), timing of peak GRF (s) (C) between non-injured and LSA groups.
3.4.6 Torso Joint Moments and Forces

There was no main effect of LSA during the front-foot contact phase for torso joint moments ($F_{1,18} = 0.02, P = 0.88, \eta^2 = 0.0012$) or forces ($F_{1,18} = 0.09, P = 0.77, \eta^2 = 0.0049$), nor their respective interactions of moments*LSA ($F_{11,198} = 1.1, P = 0.36, \eta^2 = 0.0577$; Figure 3-8A) and jforce*LSA ($F_{6,108} = 0.92, P = 0.48, \eta^2 = 0.0486$; Figure 3-8B).

The lower limb joint moments are shown in Appendix 7.9 (Figure 7-3).

![Figure 3-8](image-url) Mean (± SE) values of peak torso joint (A) moment (relative BM x height) and (B) force (relative BM) between non-injured and LSA groups.
3.5 Discussion

Fast bowling-related lumbar spine injury is often attributed to bowling technique. In contrast to our study’s hypothesis, junior fast bowlers with LSA displayed similar shoulder counter-rotation, shoulder-pelvis separation angle, trunk lateral flexion and lumbar loading during their fast bowling action compared to their counterparts with no LSA. However, new findings have emerged from this current study that add to the existing knowledge of this critical relationship between fast bowling technique and lumbar spine injury risk, and will be explored here within this discussion.

The mixed action has traditionally been attributed to the increased risk of lumbar spine injury (Elliott, 2000). The results of the present study are in line with previous research as the majority of bowlers that displayed a LSA utilised a mixed bowling action (67%) compared to only 36% of the non-injured bowlers (Portus et al., 2004; Foster et al., 1989; Elliott and Khangure, 2002). Nevertheless, this study also observed LSA in bowlers with a semi-open and front-on action (n = 2 and n = 1, respectively). These results suggest that the mixed action is not solely responsible for the development of a LSA but is due to factors common amongst these multiple action types. It should be noted that if the threshold of 40° of shoulder counter-rotation was used to define the fast bowling action here was altered to a lower threshold (e.g. 30°), this would have led to a different distribution of bowling action classification. If lumbar spine injury is to be attributed to a particular action type, it is recommended that a standardised classification system must be established and includes an agreed shoulder counter-rotation threshold.

This study found no significant difference in shoulder counter-rotation in participants with or without a LSA. However, previous research has shown that increased shoulder counter-rotation is related to increased lumbar spine injury incidence (Portus et al., 2004; Foster et al., 1989; Elliott, 2000), yet the amount of shoulder counter-rotation that has been contributed to injury incidence in this research has ranged from 20° to 40°. The lack of difference in shoulder counter-rotation questions its use as the
primary mechanism of injury among fast bowlers. Therefore, more complex factors within the fast bowling technique may be more influential on lumbar spine injury risk than shoulder counter-rotation alone.

A new critical finding of this study was the identification of the relationship of the T12-L1 joint kinematics with the presence of a LSA in junior fast bowlers. The LSA group displayed decreased T12-L1 rotational ROM between BIC and FIC when compared to the non-injured group (33 ± 3° and 41 ± 3°, respectively). This restricted movement of the LSA group during back-foot contact phase is potentially dangerous as the load transferred to the lumbar spine may not be effectively dissipated via increased ROM. Unfortunately, a limitation in the lack of force platforms access led to no kinetic analysis during the back-foot contact phase (only front-foot contact phase), thus an explanation of restricted movement on lumbar loading cannot be inferred here. It remains unclear if the restricted rotation of T12-L1 is a cause of LSA or if the presence of LSA contributes to this restricted rotation observed in the LSA group. To date no previous research has reported on T12-L1 kinematics of the bowling action, although the loading of the T12-L1 has been reported (Crewe et al., 2013), as the trunk is typically modelled as a single segment rather than a two-segment model within this study. In this study and that of Crewe et al. (2013), used the same 3D modelling methodology to analyse the trunk into a separate thoracic and lumbar segments, thus providing greater sensitivity to the mechanics of the trunk-pelvis relationship.

As the lower limb plays a crucial role in transferring load to the lumbar region (Mero et al., 1994), the front limb technique during fast bowling action may determine the attenuation of the GRFs transmitted from the front foot to the lumbar spine (Worthington et al., 2013b). Bowlers with LSA at BR utilised ~15° less knee flexion in their front limb compared to the non-injured group but this knee joint strategy did not lead to any significant differences in peak knee extension moments nor any GRF variables (peak GRF, impulse or timing to peak GRF) compared to the non-injured bowlers. These findings support previous research in adult bowlers that showed that a
more extended knee during front-foot contact is a risk factor for lumbar injury risk (Olivier et al., 2015). The lack of differences in kinetics may be due to both groups using similar knee flexion ROM from FIC to BR, whether through continued flexion or extension, so that GRFs are dissipated at comparable rates.

The position of the hip joint of the front limb could potentially affect lumbar spine injury risk. This current study observed that the LSA group displayed an internally rotated hip at AH (11 ± 4°) of their front limb, whereas the non-injured group hip joint of their front limb was in an externally rotated position (-12 ± 4°). The increased hip joint internal rotation of the front limb may be the result of the thigh segment being more internally rotated during the bowling action. While no differences were seen in front limb foot alignment, it appears to play a role by the time of arm-horizontal. It would seem that the front limb’s higher hip internal rotation is caused when the foot of that limb being aligned down the line of the pitch, changed the alignment of the thigh segment to a more internally rotated position. A longitudinal study is required to confirm or refute this notion of whether the rotation of the hip joint of the front limb contributes to the development of a LSA or is a result of a LSA.

A lack of force platform equipment and size of the force platform pit within the laboratory was a limitation in this study, with only enough force platforms to record front-foot but not back-foot contact phase during the bowling action. Therefore, it is not known whether the significant differences in T12-L1 joint kinematics seen here in this study led to changes in T12-L1 joint moments or forces and, in turn, increased lumbar spine injury risk. Two other limitations of this study were also identified. Firstly, the junior participants were inexperienced in a laboratory setting. While every attempt was made to recreate match-like conditions, the pitch surface type and the outdoor setting could not be replicated. Rather, the participants bowled indoors on a concrete surface and wearing athletic shoes. Secondly, the sample size of this cohort was an important limitation. As the focus of the study was dependent on an age-
specific demographic, this restricted the number of participants that could be recruited within a regional area.

3.6 Conclusions
While shoulder counter-rotation was not related to LSA within this cohort of junior fast bowlers, restricted T12-L1 ROM was linked to LSA. Greater knee extension at ball-release and hip joint internal rotation at arm-horizontal of the front limb within the LSA group emphasise the importance of the mechanics of the front limb during the fast bowling action with lumbar spine injury risk. The results of this current study have provided new avenues of investigation into the biomechanics of fast bowling technique and lumbar spine injury. Further investigation into lumbo-pelvic and trunk movement, as well as the front limb, is needed to provide stronger evidence that these risk factors are associated with lumbar spine injury in junior fast bowlers.

3.7 Acknowledgements
The authors of this study acknowledge Professor Robert Robergs for his assistance with the LabView software to analyse ground reaction force data, Cricket NSW for the assistance of recruiting participants and PRP Imaging for conducting the MRI scans and providing the results of the scans. It is also disclosed that funding was provided by iCare NSW to complete this study.
## INFORMATION BOX

### What is already known on this topic?
- Fast bowling is a highly complex and rapid movement which displays a high prevalence of lumbar spine injury among senior and junior athletes.
- The mixed bowling action is commonly cited as the fast bowling action attributed to increased risk to lumbar spine injury.
- The variables associated with lumbar spine injury include: shoulder counter-rotation, shoulder-pelvis separation angle, trunk lateral flexion and an extended front knee.

### What this study adds?
- Fast bowlers that showed LSAs had restricted T12-L1 range of motion during the back-foot contact phase of the fast bowling action.
- The role of the knee and hip joints of the front limb is likely to influence or be influenced by LSA risk.
3.8 References


Chapter 3: Manuscript 2


Context of Manuscript in Relation to the Thesis

Research into injuries sustained by fast bowlers has increased over the previous decade. This increased research is due to the high incidence of lumbar spine injuries experienced by fast bowlers. It has been shown that lumbar spine abnormalities in junior fast bowlers including bone oedema that is a known predictor of severe lumbar spine injuries such as stress fractures, which was explored in Manuscript 2. Nevertheless, while Manuscript 2 explored risk factors for lumbar injury during the fast bowling including the mixed bowling action, trunk lateral flexion and shoulder-counter-rotation, but these biomechanical variables cannot account for the occurrence of all lumbar spine injuries. The findings of Manuscript 2 indicated that LSA was potentially related to limited T12-L1 rotational range of motion, and knee joint extension and hip joint internal rotation during the bowling action. These biomechanical variables and the spinal joint angles and peak joint forces and moments reported within Manuscript 2 do not provide sufficient evidence to explain the relationship between LSA and bowling technique. Further exploration of this relationship to include the relative velocity of the 3D-planar motion of the trunk and pelvis is needed to give a stronger indication of the relationship of these segments during fast bowling and its relationship to LSA. That is, as the trunk and pelvis undergo high velocities during the fast bowling action, it stands to reason that a relationship between the magnitude and timing of the velocities of these two critical segments within the fast bowling action that may influence lumbar spine injury risk. In golf, it has been shown that the combined velocity of the trunk and pelvis is measured via the ‘crunch factor’ and is related to the shear and compressive joint loads placed on the lumbar spine. Therefore, this manuscript builds upon the aims of this thesis of lumbar spine injury risk in junior fast bowlers by exploring these 3D relative planar motion relationships with lumbar spine abnormalities via ‘crunch factor’ analysis within this cohort.
Chapter 4: ‘Crunch factor’ and the magnitude of its variability within the fast bowling action relationship to injury in junior fast bowlers.

This chapter is an amended version of the manuscript: Schaefer, A., Ferdinands, R.E.D., O’Dwyer, N., & Edwards, S. ‘Crunch factor’ and the magnitude of its variability within the fast bowling action relationship to injury in junior fast bowlers. To be submitted to the Journal of Biomechanics.

4.1 Abstract

Background: The fast bowling action involves complex movement and timing of the trunk and pelvis segments in multiple planes of motion to maximise bowling performance and minimise injury risk. The relationships of these multi-planar segment motions during bowling measured by the ‘crunch factor’ has been proposed to predict lumbar spine load, and in turn injury risk.

Aim: The study’s purpose was to investigate the relationship between lumbar spine loading and abnormalities with multi-segment crunch factor analyses and magnitude of crunch factor variability of the junior fast bowling action.

Methods: Three-dimensional (3D) kinematic and kinetic data were collected from 20 male junior fast bowler’s action during a five-over spell at match pace. Crunch factor analysis was conducted by the multiplication of segment angular velocities in a combination of the trunk and pelvis segments. Bivariate Pearson’s product-moment correlation were performed to assess the relationship between crunch factor with L5-S1 and T12-L1 joint moments and forces. Mixed-design factorial analyses of variance were performed to assess between-group differences in lumbar spine abnormalities (LSA) with crunch factor, and the variability of its magnitude during the bowling action. Magnetic resonance imaging was conducted to determine if a LSA was present on diagnostic imaging for each participant.
Results: Higher crunch factor (trunk flexion/extension-pelvis rotation) was significantly correlated with increased L5-S1 and T12-L1 joint mediolateral shear forces but reduced compressive forces during the bowing action. Yet, no significant link was observed between LSA and any of the crunch factors mean values nor its magnitude of its variability within the bowling action.

Conclusions: It appears trunk flexion coupled with right pelvis rotation is correlated with spinal mediolateral shear joint forces, which may be detrimental to spinal health in junior fast bowlers. Nevertheless, the lack of between-group differences in any crunch factor variables in bowlers with and without LSA questions the importance of this type of analysis to accurately identify bowlers at risk of spinal injury.

4.2 Introduction
Fast bowling is a highly complex movement, requiring the individual to project a ball towards the batsman at the maximum velocity, in excess of 140km·h$^{-1}$ (Worthington et al., 2013). Producing high ball velocities creates a large amount of stress on the body, leading to an increased risk of injury (Stretch and Orchard, 2003). Common lumbar spine overuse injuries include spondylolysis, spondylolisthesis, pedicle sclerosis intervertebral disc degeneration, and stress fractures (Elliott et al., 1992; Foster et al., 1989; Glazier, 2010; Portus et al., 2004). The incidence of lumbar spine injury is particularly high for both senior (53%) and junior (24%) fast bowling athletes (Dennis et al., 2005; Elliott and Khangure, 2002; Stretch and Orchard, 2003). It is often cited that the mixed bowling action is responsible for the increased risk of lumbar spine injury (Elliott, 2000; Portus et al., 2004).

The mixed bowling action, shown to increase injury risk, typically displays greater multi-planar motion compared to the other bowling action types. To quantify the role of multi-planar motion and its relationship to spinal injury risk in sporting activities, recent research has begun to explore the concept of ‘crunch factor’ (Cole and Grimshaw, 2014). The definition of ‘crunch factor’ ranges from the instantaneous
product of single-segment lateral flexion and rotation velocity (Glazier, 2010; Middleton et al., 2016; Portus et al., 2017; Sugaya et al., 1996), to more complex multi-segment products velocities in all three planes of motion (Ferdinands et al., 2014b). In golf, crunch factor definitions of the trunk (left/right lateral flexion and left/right rotation) multiplied by the pelvis (flexion/extension and left/right rotation) velocity were related with high lumbar flexion and rotation moments (Ferdinands et al., 2014b). This combination of high crunch factor and loading is thought to lead to a greater likelihood of lumbar spine injury in golf (Ferdinands et al., 2014b). With golf demonstrating that crunch factor is related to lumbar load in multi-planar movements, it could be inferred that this analysis can be applied to other multi-planar movements such as cricket fast bowling.

It has been proposed in fast bowling that crunch factor analysis can be employed as a new methodology to assess biomechanical risk factors for sustaining a lumbar spine injury in cricketers (Glazier, 2010). During the fast bowling action, the trunk and pelvis segments undergo rotation in all three planes (Bartlett et al., 1996). Theoretically, an analysis of crunch factor should assist in assessing lumbar load through the movement of the trunk and pelvis segments during the fast bowling action, especially as spinal range of motion decreases and stiffness increases when moving down the spinal column (Busscher et al., 2009). A ‘spin bowling’ case study by Middleton et al. (2016) found that an adult bowler with a low back pain caused by a lumbar stress fracture demonstrated a greater trunk (lateral flexion-rotation) crunch factor by these authors when bowling with an ‘off-break’ technique compared to other spin bowling variations.

The limitations of a case study design along with only a single-segment calculation of thorax crunch factor provides weak evidence to the role of crunch factor and injury risk in bowling (Middleton et al., 2016). In contrast, Portus et al. (2017) crunch factor analysis of junior and senior fast bowlers found no link between single-segment pelvis, lumbar spine and thorax crunch factors with lumbar spine injury. The authors believed that a relationship may still exist between crunch factor and injury but cited a lack of
statistical findings due to the high magnitude of variability within the cohort and a low sample size influencing results (Portus et al., 2017). It is likely that the single-segment crunch factor analysis by Middleton et al. (2016) and Portus et al. (2017) reduces the opportunity to identify a connection between crunch factor and lumbar spine injury in this multi-planar movement. As the lumbar spine interconnects the trunk and pelvis, the movement of the lumbar spine is likely dependent on the motion of the combination these two segments.

Movement variability is another key concept explored in relation to performance (Glazier, 2011) and overuse injuries (Hamill et al., 2012; James et al., 2000) that affords an new alternative method to offer new insight into the injury risk and bowling technique relationship. An underlying factor associated with overuse low back injuries has suggested that low movement variability when performing a repeated motor pattern leaves the body more rigid and inflexible, due to decreased complexity via reduced degrees of freedom of movement (Hamill et al., 2012; Seay et al., 2011; Stergiou et al., 2006). Therefore, overuse injury risk may increase due to decreased movement variability due to repeated loads on the same tissue (Hamill et al., 2012) and less time between loading events (James et al., 2000). The only research within junior fast bowling during an extended spell by Schaefer et al. (2018) has shown that the magnitude of movement variability remained unaltered. These authors reported the standard deviations of key biomechanical variables during fast bowling action as it provided a valid linear measure of the magnitude of movement variability (Harbourne and Stergiou, 2009). Though, it is not known whether fast bowlers with LSA display lower movement variability, via decrease standard deviations, of their technique than non-injured bowlers, which in turn, contributes to the development of their lumbar spine injury.

To date, only two studies have been conducted analysing the use of crunch factor and movement variability of the fast bowling technique with lumbar spine injury. The purpose of this study was to investigate the relationship between the presence of a
LSA with multi-segment crunch factor analyses and crunch factor variability magnitude of the fast bowling action in junior fast bowlers. It is hypothesised that crunch factor would be positively correlated with spinal joint moments and forces. It was also hypothesised that junior fast bowlers with a LSA would present with greater crunch factor and low crunch factor variability than their non-injured counterparts.

4.3 Methods

4.3.1 Participants

Twenty junior male fast bowlers (mean age = 13.9 ± 0.9 yr, height = 1.75 ± 0.08 m, mass = 61.6 ± 9.6 kg) judged as a fast bowler by the director of coaching for their district were recruited from within New South Wales local district and zone (pre-state) level representative teams. Participants were classified free of back pain by a qualified physiotherapist at the time of testing. Written informed consent was obtained prior to data collection from the participants and their parent/guardians, with all methods approved by the institution's Human Research Ethics Committee (2014/169; H-2015-0059).

4.3.2 Experimental Protocol

The height, body mass, and trunk and pelvis dimensions of the participant were collected, followed by a static standing trial in the anatomical position. To familiarise the participant with the laboratory environment, a standardised warm-up of balance and postural stability exercises was performed (Bird and Stuart, 2012), followed by six practice deliveries. The participants then completed the five-over spell (30 deliveries) protocol taking ~1 hour to conclude.

The bowling protocol comprised of the participant bowling at match pace (self-paced and self-selected run-up distance) on a standard cricket pitch (20.12 m). The participant attempted to land the ball at a target 6-8 m on the pitch from the
batsmen’s end. Between each over (six consecutive balls) a non-bowling period protocol was employed to replicate match conditions (Schaefer et al., 2018).

Three-dimensional (3D) data was recorded for every delivery (30 deliveries) in the five-over spell. A 15-camera motion capture system (Oqus 700+, Qualisys AB, Göteborg, Sweden) was used to record the participants’ whole body 3D motion (500 Hz). Passive reflective markers were placed on the body, for each of the lower and upper limbs, pelvis, torso and head (Figure 4-1) which included makers on the lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, the ribcage bilaterally at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker and the lumbar segment (five tracking markers) according to the protocol of Schaefer et al. (2018) and (Crewe et al., 2013). The participants wore minimal clothing (shorts) with their own socks and athletic shoes, to minimize the occlusion of the markers. The 3D ground reaction forces (GRFs) (2,000 Hz) were measured using two multichannel force platforms (Type 9281CA and 9281EA, Kistler, Winterthur, Switzerland) embedded in the floor and connected to a control unit (Type 5606, Kistler, Winterthur, Switzerland).

Figure 4-1 Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. Static markers were used for the static trial and removed for dynamic trials (including L-R 1st metatarsal, L-R medial malleolus, L-R medial femoral epicondyle) (Schaefer et al., 2018, p.10).
4.3.3 Data Reduction

All 30 deliveries of the spell were selected for the analysis to calculate all 3D kinematics and kinetics performed using Visual3D software (Version 5, C-Motion, Germantown, MD). A low-pass filter (Butterworth digital, fourth-order zero-phase with $f_c = 18$ Hz) was applied to all raw kinematic data, before individual joint kinematics during front foot-ground contact were calculated (Bisseling and Hof, 2006). All data, including raw kinematic, GRF, moment and centre of pressure data were low-pass filtered (Butterworth digital, 4th-order zero-phase with $f_c = 18$ Hz). All filtered data was utilised to calculate individual joint kinematics and net internal joint moments and forces during front foot-ground contact (Bisseling and Hof, 2006). Temporal stages for back- and front foot-ground contact during the bowling action were delineated using the filtered kinematic and kinetic data. Peak magnitudes and loading rates of GRFs were calculated using raw GRF that was low-pass filtered at 50 Hz (Butterworth digital, fourth-order zero-phase) using a customised LabView program (LabView 2010, National Instruments Corporation, Austin, USA).

Segment masses and inertial properties for the foot, shank, thigh, upper arm, forearm, hand and head segments and estimations of joint centres were defined according to (Schaefer et al., 2018). The Cartesian local coordinate system sign convention definitions were the x-axis as the mediolateral axis, the y-axis as the anterior-posterior axis and the z-axis as the superior-inferior axis. Cardan sequences of rotation for inter-segmental joint angles for ankle, knee, hip, L5-S1, T12-L1, shoulder, elbow and wrist were calculated as those reported in the protocol by Schaefer et al. (2018).

4.3.4 Data Analysis

The temporal variables of the bowling action were defined using kinematic and kinetic data and confirmed by visual inspection for analysis. These variables included back-foot initial foot-ground contact (BIC), front-foot initial ground contact (FIC), time of the peak vertical GRF ($F_V$), bowling upper-arm horizontal backwards (AH), ball release
(BR), and bowling upper-arm vertically downwards (AV) (Figure 4-2) (Schaefer et al., 2018). The back-foot contact phase is defined from BIC to FIC, whereas the front-foot contact phase is defined from FIC to AV. The definition of segmental angles were based according to Ferdinands et al. (2010), which included pelvis alignment, pelvis counter-rotation, shoulder alignment, shoulder counter-rotation and shoulder-pelvis separation angle. Classification parameters of the bowling action were implemented to classify the fast bowling action as side-on, front-on, semi-open or mixed according to Ferdinands et al. (2014a).

Figure 4-2 Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer et al., 2018).

Inverse dynamics were used to estimate net internal joint forces and moments, and peak GRFs variables calculated during the front-foot contact phase. Kinetic data during the front-foot contact phase were excluded from statistical analysis when the participant’s front-foot did not wholly contact the force platforms during that corresponding trial (unsuccessful trials = 25.8 ± 16.1%). Peak net internal joint moments were normalised to body mass multiplied by height (relative BM x height), and L5-S1 and T12-L1 joint forces were normalised to body weight (relative BW). As researchers often use the incorrect assumption that GRF variables infer joint loading, both GRF and joint loading variables were included within this analysis (Edwards et al., 2014).

A number of factors were used to quantify ‘crunch factors’ that are potentially related to fast bowling LSA based on and expanded upon the crunch factor definitions utilised previously in Ferdinands et al. (2014b). Eight crunch factors were calculated by
multiplying various combinations of planar pelvis and thorax angular velocities (Table 4-1). More crunch factors were derived by multiplying the basic crunch factors with peak vertical GRF (BW) and peak shoulder-pelvis separation angle (°). These ‘combined crunch factors’ also take into account the effect of loads, either directly through ground reaction forces, or indirectly through the pelvis-shoulder separation angle, which generates torsional stress on the lumbar spine. All crunch factor data were reported between BIC to FIC, FIC to BR and BR to AV, and also at the time of peak vertical GRF and peak shoulder-pelvis separation angle.

Table 4-1 Definition of Thoraco-pelvic and Pelvic crunch factors using segment angular velocities.

<table>
<thead>
<tr>
<th>Crunch Factor</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trunk Crunch Factors</strong></td>
<td></td>
</tr>
<tr>
<td>CF1 (Trunk\textsubscript{flex-ext}-Trunk\textsubscript{lat flex})</td>
<td>Trunk flexion/exten\textsubscript{sion} multiplied by trunk left/right lateral flexion.</td>
</tr>
<tr>
<td><strong>Thoraco-pelvic Crunch Factors</strong></td>
<td></td>
</tr>
<tr>
<td>CF2 (Trunk\textsubscript{flex-ext}-Pelvic\textsubscript{rot})</td>
<td>Trunk flexion/exten\textsubscript{sion} multiplied by pelvis left/right rotation.</td>
</tr>
<tr>
<td>CF3 (Trunk\textsubscript{lat ext}-Pelvic\textsubscript{rot})</td>
<td>Trunk left/right lateral flexion multiplied by pelvis left/right rotation.</td>
</tr>
<tr>
<td>CF4 (Trunk\textsubscript{flex-ext}-Trunk\textsubscript{lat flex-} Pelvic\textsubscript{rot})</td>
<td>Trunk flexion/exten\textsubscript{sion} multiplied by trunk left/right lateral flexion multiplied by pelvis left/right rotation.</td>
</tr>
<tr>
<td><strong>Pelvic Crunch Factors</strong></td>
<td></td>
</tr>
<tr>
<td>CF5 (Pelvic\textsubscript{flex-ext}-Pelvic\textsubscript{lat flex})</td>
<td>Pelvis flexion/exten\textsubscript{sion} multiplied by pelvis left/right flexion.</td>
</tr>
<tr>
<td>CF6 (Pelvic\textsubscript{flex-ext}-Pelvic\textsubscript{rot})</td>
<td>Pelvis flexion/exten\textsubscript{sion} multiplied by pelvis left/right rotation.</td>
</tr>
<tr>
<td>CF7 (Pelvic\textsubscript{lat flex}-Pelvic\textsubscript{rot})</td>
<td>Pelvis left/right lateral flexion multiplied by pelvis left/right rotation.</td>
</tr>
<tr>
<td>CF8 (Pelvic\textsubscript{flex-ext}-Pelvic\textsubscript{lat flex-} Pelvic\textsubscript{rot})</td>
<td>Pelvis flexion/exten\textsubscript{sion} multiplied by pelvis left/right lateral flexion multiplied by pelvis left/right rotation.</td>
</tr>
</tbody>
</table>

4.3.5 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) was performed for all participants of the lumbar spine at the beginning of the season to assess whether the participant displayed a
presence of any LSA on diagnostic imaging. The MRI scans were performed by the one radiology clinic using GE Signa 1.5T (HDe, HDx & 360) machine (GE Medical Systems, Milwaukee, Wisconsin). A phased-array spinal coil was utilised for sagittal and axial images to optimize visualization of the individual pars of the L1 to L5 vertebrae. Sagittal T2- and T1-weighted and short tau inversion recovery (STIR) sequences were performed at field of view (FOV) 28.0cm, 4mm slice thickness and 0.5 mm spacing (TR 3480ms, TE 102ms, ETL 21, 480 x 256 matrix, NEX 3 for T2 FRFSE weighting; TR 655ms, TE minimum full, ETL 2, 352 x 224 matrix, NEX 2 for T1 FSE weighting; TR 3525ms, TE 45ms, TI 145ms, 288 x 192 matrix, NEX 3 for STIR weighting). Axial sequences consisted of T2-weighted imaging from the inferior end-plates of L3 to S1 at FOV 20.0cm, 4mm slice thickness and 0.5 mm spacing (TR 5420ms, TE 90ms, ETL 19, 352 x 224 matrix, NEX 3, Phase FOV 0.80 for T2 FRFSE weighting). An axial sequence was also performed at higher levels where stress related signal was identified. The coronal imaging consisted of T1-weighted fat saturated (FS) 3D to visualise the whole vertebral column from L1 to S2. The 3D SPoiled GRASS (SPGR) CHEmical Shift Selective Pulses (CHESS) FS sequences were performed at FOV 32.0cm, 2.0mm slice thickness 60 locs to the slab (Flip angle 12, TE In Phase, 256 x 192 matrix, NEX 2, Phase FOV 0.70). These images were then reconstructed in all three planes to view the cortical bone of the pars. Coronal STIR sequences were performed to visualise the pars of the vertebrae and sacroiliac joints at FOV 29.0cm, 4 mm slice thickness and 0.5 mm spacing (STIR weighting TR 4775ms, TE 45ms, TI 145ms, 288x192 matrix, 3 NEX). All scans were assessed independently by one experienced radiologist for the presence of LSA.

4.3.6 Statistical Analysis

Based on the MRI results participants were separated into either a non-injured or LSA group, with all statistical analysis for all variables were conducted for these groups. Means and standard deviations were calculated for all variables during the fast bowling action for all overs. The mean values provided measures of crunch factor patterns across participants, while the within-participant standard deviations provided a valid
linear measure of the magnitude of movement variability (Harbourne and Stergiou, 2009). To determine significant changes ($P < 0.05$) in means for all variables mixed-design factorial analyses of variance (ANOVAs) were utilised. Outcome variables were split into crunch factors and pelvic crunch factors for the primary test of the effect of LSA. There were three factors for analyses for crunch factors and pelvic crunch factors (factor*event*LSA). In the result of significant effects, the implementation of Tukey post hoc tests were conducted to identify the precise variable attributed to the significant interaction. All ANOVAs were carried out using Statistica (v.13, StatSoft Inc., Tulsa, OK, USA). Effect sizes were calculated for the ANOVAs using partial eta squared for all interactions. Effects sizes ($\eta_p^2$) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson, 2011). Intrasubject coefficient of variation (CV) for the standard deviation of the crunch factors were calculated by dividing the standard deviation about the mean for each trial (Raj et al., 2017). If the ratio of the CV between the two groups differed when compared differed by a factor of greater than 1.15 or less than 0.85, it was deemed substantial (Hopkins and Hewson, 2001). To satisfy the assumptions of normality of distribution and sphericity, the data was first checked and in cases of violations of the latter, multivariate ANOVA was used.

A bivariate Pearson’s product-moment correlation ($P < 0.05$) was calculated between thoraco-pelvic crunch factors and lumbar region joint moments and forces using Statistica (v.10, StatSoft Inc., Tulsa, OK, USA) and classified according to (Hopkins et al., 2009) (0.0-0.1 = trivial, 0.1-0.3 = small, 0.3-0.5 = moderate, 0.5-0.7 = large, 0.7-0.9 = very large, 0.9-1.0 = extremely large).
4.4 Results

4.4.1 Action Classification and LSA

The action classification of the current cohort was broken down into side-on action \( n = 1 \) (5%), front-on action \( n = 5 \) (25%), semi-open action \( n = 4 \) (20%) and mixed action \( n = 10 \) (50%), with the distribution of injury status seen in Table 4-2.

Table 4-2: Distribution of injury among action types for the non-injured and LSA group. Percentage breakdown of total action types per group.

<table>
<thead>
<tr>
<th>Action type</th>
<th>Non-Injured (n=11)</th>
<th>LSA (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-on</td>
<td>1 (9%)</td>
<td>0</td>
</tr>
<tr>
<td>Front-on</td>
<td>4 (36%)</td>
<td>1 (11%)</td>
</tr>
<tr>
<td>Semi-open</td>
<td>2 (18%)</td>
<td>2 (22%)</td>
</tr>
<tr>
<td>Mixed</td>
<td>4 (36%)</td>
<td>6 (67%)</td>
</tr>
</tbody>
</table>

4.4.2 Crunch Factor and Spinal Load

Representative sample means (± SD) of the thoraco-pelvic crunch factors of a single participant are shown in Figure 4-3. Crunch factor and lumbar moments and joint forces during front-foot contact phase were not correlated with any crunch factor and L5-S1 and T12-L1 joint moments. Joint forces during front-foot contact phase were significantly correlated with Crunch Factors 2 (Trunk\_flex-ext-Pelvic\_rot) as seen in Figure 4-4A-C, Figure 4-5A-C and Figure 4-6A-B, and Crunch Factor 4 (Trunk\_flex-ext-Trunk\_lat\_flex-Pelvic\_rot) as seen in Figure 4-7A-B (p-values and r shown in figure), while no other significant correlations were observed for Crunch Factors 1,3 or 5-8.
Figure 4-3  CF1 (Trunk flex-ext-Trunk lat flex) (A), CF2 (Trunk flex-ext-Pelvic rot) (B), CF3 (Trunk lat ext-Pelvic rot) (C) and CF4 (Trunk flex-ext-Trunk lat flex-Pelvic rot) (D) from BIC to AV. Black X = FlC, green X = FV, blue X = Peak shoulder-pelvis separation, mean (solid line) and standard deviation (shaded area) of five-over spell.
Figure 4-4  Significant correlations of CF2 (Trunk flex-ext-Pelvic rot) with L5-S1 mediolateral force at FV (A), L5-S1 compressive force at FIC-BR (B) & FV (C).
Figure 4-5 Significant correlations of CF2 (Trunk flex-ext-Pelvic rot) with T12-L1 compressive force at FIC-BR (A), FV (B) & Sh-Pel Sep (C).
Figure 4-6 Significant correlations of CF2 (Trunk<sub>flex-ext</sub>-Pelvic<sub>rot</sub>) with T12-L1 mediolateral force at FV (A) & Sh-Pel Sep (B).
Figure 4-7  Significant correlations of CF4 (Trunk flex-ext-Trunk lat flex-Pelvic rot) with T12-L1 compressive force at FIC-BR (A) & FV (B).
4.4.3 Crunch Factor and LSA

No main effect resulted from thoraco-pelvic \( (F_{1,18} = 0.2, P = 0.66, \eta^2_p = 0.0107) \) or pelvic \( (F_{1,18} = 1.04, P = 0.32, \eta^2_p = 0.0544) \) crunch factor variables for LSA, nor any significant interactions for factor*event*LSA \( (F_{12,216} = 0.32, P = 0.98, \eta^2_p = 0.0177; \text{Figure 4-8A}) \) or \( (F_{12,216} = 1.05, P = 0.4, \eta^2_p = 0.0553; \text{Figure 4-8B}) \), respectively.

**Figure 4-8** Mean (± SE) thoraco-pelvic (A) and pelvic (B) crunch factors for non-injured (Non-Inj) and LSA groups. Note: CF4 (Trunk flex-ext-Trunk lat flex-Pelvic rot), and CF8 (Pelvic flex-ext-Pelvic lat flex-Pelvic rot) are scaled to right Y-axis.
4.4.4 Crunch Factor multiplied by Peak GRF

For the combined crunch factor analysis with peak vertical GRF, the main effect of LSA resulted in no significant results for thoraco-pelvic crunch factor ($F_{1,18} = 0.0004, P = 0.99, \eta^2_p = 0.0000$) and no significant interaction for factor*event*LSA was observed ($F_{12,216} = 0.5, P = 0.92, \eta^2_p = 0.0269$; Figure 4-9A). The results of pelvic crunch factors returned no main effect of LSA ($F_{1,18} = 1.3, P = 0.27, \eta^2_p = 0.0672$) nor factor*event*LSA interaction ($F_{12,216} = 1.32, P = 0.21, \eta^2_p = 0.0681$; Figure 4-9B).

![Figure 4-9](image-url)

Figure 4-9: Mean (± SE) of combined crunch factors for peak GRF with thoraco-pelvic crunch factors (A) and pelvic crunch factors (B) for non-injured (Non-Inj) and LSA groups. Note: CF4 (Trunk flex/Trunk lat flex) and CF8 (Pelvic flex/Pelvic rot) are scaled to right Y-axis.
4.4.5 Crunch Factor multiplied by Shoulder-Pelvis Separation Angle

For the combined crunch factors analysis with shoulder-pelvis separation angle, no main effect of LSA was observed for thoraco-pelvic crunch factors ($F_{1,18} = 0.2$, $P = 0.68$, $\eta^2_p = 0.01$) or pelvic crunch factors ($F_{1,18} = 0.87$, $P = 0.36$, $\eta^2_p = 0.0459$), nor any significant interactions observed for factor*event*LSA ($F_{12,216} = 0.36$, $P = 0.97$, $\eta^2_p = 0.0198$; Figure 4-10A) or ($F_{12,216} = 1.05$, $P = 0.4$, $\eta^2_p = 0.0552$; Figure 4-10B), respectively.

![Figure 4-10](image)

Figure 4-10 Mean (± SE) of combined crunch factors for peak shoulder-pelvis separation angle interaction with thoraco-pelvic crunch factors (A) and pelvic crunch factors (B) for non-injured (Non-Inj) and LSA groups. Note: CF4 (Trunk flex-ext*Trunk lat flex*Pelvic rot), and CF8 (Pelvic flex-ext*Pelvic lat flex*Pelvic rot) are scaled to right Y-axis.
4.4.6 Crunch Factor Variability and injury

The results of the intrasubject CVs of crunch factors are presented in Table 4-3. The results of variability for thoraco-pelvic crunch factors indicated no main effect of LSA ($F_{1,18} = 0.05, P = 0.83, \eta^2_p = 0.0025$), nor any significant interaction for factor*event*LSA ($F_{12,216} = 0.17, P = 0.99, \eta^2_p = 0.0094$; Figure 4-11A). Pelvic crunch factor variability had no significant main effect of LSA ($F_{1,18} = 0.42, P = 0.53, \eta^2_p = 0.0227$) nor a significant interaction for factor*event*LSA ($F_{12,216} = 1.01, P = 0.44, \eta^2_p = 0.053$; Figure 4-11B).

Based on the ratios of CVs between-groups, the LSA group displayed higher variability for Crunch Factor 1 (Trunk flex-ext*Trunk lat flex) and Crunch Factor 4 (Trunk flex-ext*Trunk lat flex-Pelvic rot) at BIC-FIC, whereas Crunch Factor 2 (Trunk flex-ext*Pelvic rot) displayed higher variability at FIC-BR but lower variability at BR-AV compared to the non-injured group.

Lower variability was observed by the LSA group when compared to the non-injured group at Crunch Factor 5 (Pelvic flex-ext*Pelvic lat flex) at FV, Crunch Factor 6 (Pelvic flex-ext*Pelvic rot) at BR-AV, Crunch Factor 7 (Pelvic lat flex-Pelvic rot) at BR-AV and FV, and Crunch Factor 8 (Pelvic flex-ext*Pelvic lat flex*Pelvic rot) at BR-AV.
Table 4-3  Intra-subject coefficient of variations (%) of crunch factors (CF1-CF8) for non-injured (Non-Inj) and LSA groups. The LSA group displaying lower (>1.15) or higher (<0.85) variability than non-injured group. CF1 (Crunch Factor 1, Trunk flex-ext-Trunk lat flex), CF2 (Crunch Factor 2, Trunk flex-ext-Pelvic rot), CF3 (Crunch Factor 3, Trunk lat ext-Pelvic rot), CF4 (Crunch Factor 4, Trunk flex-ext-Trunk lat flex Pelvic rot), CF5 (Crunch Factor 5, Pelvic flex-ext-Pelvic lat flex), CF6 (Crunch Factor 6, Pelvic flex-Pelvic lat flex), CF7 (Crunch Factor 7, Pelvic flex-Pelvic lat flex-Pelvic rot) and CF8 (Crunch Factor 8, Pelvic flex-ext-Pelvic lat flex-Pelvic rot).

<table>
<thead>
<tr>
<th></th>
<th>BIC-FIC</th>
<th>FIC-BR</th>
<th>BR-AV</th>
<th>FV</th>
<th>SH-PEL SEP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-Inj</td>
<td>LSA</td>
<td>CV ratio</td>
<td>Non-Inj</td>
<td>LSA</td>
</tr>
<tr>
<td>CF1</td>
<td>19.2</td>
<td>29.7</td>
<td>0.65*</td>
<td>18.8</td>
<td>18.6</td>
</tr>
<tr>
<td>CF2</td>
<td>24.1</td>
<td>25.8</td>
<td>0.93</td>
<td>11.4</td>
<td>13.6</td>
</tr>
<tr>
<td>CF3</td>
<td>19.3</td>
<td>22.6</td>
<td>0.85</td>
<td>19</td>
<td>20.3</td>
</tr>
<tr>
<td>CF4</td>
<td>25.2</td>
<td>36.3</td>
<td>0.69*</td>
<td>22.8</td>
<td>24.1</td>
</tr>
<tr>
<td>CF5</td>
<td>29</td>
<td>27.9</td>
<td>1.04</td>
<td>27.8</td>
<td>27.2</td>
</tr>
<tr>
<td>CF6</td>
<td>23</td>
<td>22</td>
<td>1.05</td>
<td>16.8</td>
<td>19.1</td>
</tr>
<tr>
<td>CF7</td>
<td>29.3</td>
<td>28.5</td>
<td>1.03</td>
<td>23.6</td>
<td>22</td>
</tr>
<tr>
<td>CF8</td>
<td>37.3</td>
<td>35.4</td>
<td>1.05</td>
<td>30.9</td>
<td>31.6</td>
</tr>
</tbody>
</table>
Figure 4-11 Mean (± SE) variability for thoraco-pelvic (A) and pelvic (B) crunch factors for non-injured (Non-Inj) and LSA groups. Note: CF4 (Trunkflex-ext-Trunklat flex-Pelvicrot), and CF8 (Pelvicflex-ext-Pelviclat flex-Pelvicrot) are scaled to right Y-axis.

4.5 Discussion
Crunch factor analyses was chosen to examine spinal joint loading and injury relationship within this current study as fast bowling involves high angular segment velocities of the trunk and pelvis. Due to the unclear relationship of multi-segment
crunch factor analysis between the trunk and pelvis during fast bowling, the aim of this study was to investigate this relationship and its variability during the fast bowling action with spinal loading and LSA.

The time-series graph displayed in Figure 4-2 outlines the pattern of the Crunch Factors 1 to 4 over the fast bowling action from back-foot initial contact to arm vertically down. Upon qualitative analysis of the crunch factor patterns, it appears that peak vertical GRF and peak shoulder-pelvis separation angle occur simultaneously with the peak of each crunch factor. The examination of the crunch factor pattern would suggest that the lumbar spine is placed in a higher multi-planar load when the vertical GRF and the shoulder-pelvis separation angle are at their highest. The higher the magnitude of lumbar spine loading at these time points seemingly validate the use of crunch factor data to identify potential injury risk when junior fast bowlers are more susceptible to sustaining lumbar spine injury.

This study also investigated possible correlations of the crunch factors with L5-S1 and T12-L1 joint moments and forces. Thoraco-pelvic Crunch Factor 2 (Trunk\(\text{flex-ext}\)-Pelvic\(\text{rot}\)) was positively correlated with higher lateral shear joint force for L5-S1 and T12-L1 at the time of FV and for T12-L1 at the time of peak shoulder-pelvis separation angle (Figure 4-3A & Figure 4-5 A & B, respectively). This positive correlation of lateral shear force and thoraco-pelvic Crunch Factor 2 (Trunk\(\text{flex-ext}\)-Pelvic\(\text{rot}\)) suggests that higher net magnitude of trunk flexion and pelvis rotation velocity lead to higher spinal lateral shear joint force. This is of concern as modelling of the spine shows that increased lateral shear strain is linked with greater risk of spinal injury (Costi et al., 2007).

Another crunch factor was also found to be correlated with compressive forces of the L5-S1 and T12-L1 joints. A higher Crunch Factor 2 (Trunk\(\text{flex-ext}\)-Pelvic\(\text{rot}\)) was correlated with lower compressive force at L5-S1 and T12-L1 joints between the time period from front-foot initial contact to ball release and at the time of the peak GRF (Figure 4-3 B-C & Figure 4-4 A-B), and lower T12-L1 compressive force at the time of the peak
shoulder-pelvis separation angle (Figure 4-4C). Similarly, higher Crunch Factor 4 (Trunk\textsuperscript{flex-ext} - Trunk\textsuperscript{lat flex} - Pelvic\textsuperscript{rot}) was correlated with lower T12-L1 compressive force between the time period from front-foot initial contact to ball-release and at the time of the peak GRF (Figure 4-6). It would appear that the trunk flexion component of both Crunch Factor 2 and 4 contributes to decreased compressive force as the space between vertebrae increases leading to a decrease in the compressive force. Therefore, a trade-off exists whereby a decrease in the compressive force produces an increase in the lateral shear joint force. That is, an increased crunch factor exists as the movement of the trunk works to reduce compressive force, but this decrease is counteracted by the increase in pelvis rotation that leads to an increase mediolateral shear force. Further investigation is needed to establish if action type has an effect on these crunch factors and spinal loading.

Peak magnitude of the crunch factors during any of the three phases were not correlated with increased lateral shear joint force during the fast bowing action. Peak crunch factors were utilised in this current study as greater peak velocities would suggest increased magnitude of positive and negative accelerations. The use of peak crunch factors should then be able to inform the level of joint loading through the inverse dynamics equations. The magnitude of crunch factor may not be influential to spinal load but rather the rate at which the crunch factor increases may be of greater importance.

The timing of the significantly higher crunch factor and the lateral shear joint force occurs during the bowling action is of importance. Crunch factors 2 and 4 at the specific time point of the peak vertical GRF was correlated with higher lateral shear joint force (Figure 4-2B & D). This relationship may influence lumbar spine injury risk, as greater trunk and pelvis motion is coupled with higher spinal lateral shear joint force at the time of peak vertical GRF during fast bowling, requiring the lumbar spine to withstand multiple kinetic variables that peak at a similar time point. These results highlight the
complexity of the fast bowling action mechanics and suggests that 2D kinematics may not effectively assess the stress placed on the lumbar spine and in turn, injury risk.

While crunch factor was related to lumbar load during the fast bowling action in this current study, crunch factor was not significantly connected to the presence of a LSA. High variability of the crunch factor has been identified as influencing findings regarding its relation with lumbar spine injury risk (Portus et al., 2017), a finding supported by this current study but only during the early phase of the bowling action. It should be noted that the LSA group displayed lower variability at peak vertical GRF compared to their non-injured counterparts (Table 4-3), which is known to be associated with low back pain (Seay et al., 2011). It is likely that the high crunch factor variability observed within this current study is attributed to the multiplication of velocities, which amplifies the amount of noise of this first derivative data compared to positional data, leading to larger amount of noise in the velocity data (D’Amico and Ferrigno, 1990). Rather, other variables such as angular displacements should be considered to calculate crunch factors to reduce variability due to noise amplification.

To assess whether the magnitude of variability differed between groups, the crunch factors were also analysed in terms of coefficient of variance and standard deviation of the biomechanical variables of the fast bowling action. The coefficient of variance were found to be highest after ball-release during the follow-through phase of the action (Table 4-3). The higher crunch factors during the follow-through phase may indicate that the risk of lumbar spine injury in fast bowling are present after ball-release. Future research should therefore explore risk factors for lumbar injury during the follow-through. No significant differences were seen between the magnitude of variability of crunch factor and the presence of a LSA, however the ratio of the CVs observed substantial results. Variability indicated by the ratio of the crunch factors CVs revealed that the LSA group versus the non-injured group were noted to display higher variability in two variables during back-foot to front-foot contact phase (CF1 & CF4, Table 4-3), yet displayed lower variability in four variables during the phase from
ball release to bowling arm vertical (CF2, CF6, CF7 & CF8, Table 4-3). Therefore, the magnitude of variability may not be as important to LSA as the coordination of the trunk and pelvis segments. It has been shown that coordination variability is related to low back pain in gait when the trunk and pelvis are moving in the same direction (in-phase), rather than in opposite directions (out-phase; e.g. trunk right rotates, as the pelvis left rotates) (Seay et al., 2011). Therefore, it may be acceptable for the trunk and pelvis segments to move in opposing motions in the same plane without risking injury.

A potential limitation of using crunch factor to explain injury risk is that it is unclear which specific biomechanical variable is contributing to the magnitude of the crunch factor. For example, a participant in this cohort with a bilateral stress fracture was hypothesised to display a high crunch factor, yet this participant displayed one of the lowest magnitude of the crunch factor within this cohort. This low magnitude of the crunch factor was due to the pelvis segment demonstrating low axial rotation velocity during the bowling action, resulting in lower crunch factor magnitude. Therefore, a revision of crunch factor calculation to account for when one segment remains stationary or with a low velocity whilst the other segment utilises a high segment velocity, may be required to find links with lumbar spine injury risk. Another principal limitation of this study was the relative small sample size, further limited when split into two groups. One reason for this was the restricted range of age group targeted for analysis, which limited the number of participants that could be recruited for testing and were willing to travel to be tested within a regional location. The decreased power resulting from the small sample size may have confounded any significant results that have been otherwise seen with a larger sample group.

4.6 Conclusions
This study investigated the relationship between multi-segment crunch factor analyses and bowling action, with no link between crunch factor and the presence of a LSA observed in a cohort of junior fast bowlers. A key finding of this study was that thoraco-
lumbar Crunch Factors 2 and 4 were significantly correlated with L5-S1 and T12-L1 joint forces, particularly during peak vertical GRF, suggesting that a multi-segment crunch factor analysis may be a viable tool in predicting spinal load. Crunch factor analysis was not significantly related to the presence of LSA in fast bowlers potentially due to high variability, yet lower variability is present during the period of peak vertical GRF and after ball-release in the LSA group. Therefore, crunch factor analysis needs to be refined in order negate the impact of variability and identify which segment contributes to high crunch factor during fast bowling. As sample size and high variability were mitigating factors of this study, future research is needed on a substantial sample size to rule out crunch factor variability and the effects of lumbar spine injury.

4.7 Acknowledgements
The authors of this study acknowledge Professor Robert Robergs for his assistance with the LabView software to analyse ground reaction force data, CricketNSW for the assistance of recruiting participants and PRP Imaging for conducting the MRI scans and providing the results of the scans. It should also be disclosed that funding was provided by iCare NSW to complete this study.

**INFORMATION BOX**

<table>
<thead>
<tr>
<th>What is already known on this topic?</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Fast bowling is highly complex and rapid movement that displays a high prevalence of lumbar spine injury among senior and junior athletes</td>
</tr>
<tr>
<td>- ‘Crunch factor’ analysis has been proposed as a risk factor of lumbar spine injury in activities involving multi-planar motion including golf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What this study adds?</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Multi-segment crunch factor analysis during fast bowling found correlations with higher mediolateral spinal joint shear force but lower compressive spinal joint force in junior bowlers.</td>
</tr>
<tr>
<td>- No link was observed between multi-segment crunch factor and lumbar spine abnormality within a cohort of junior fast bowlers but lower variability is observed in the LSA group during peak vertical GRF and after ball-release during fast bowling.</td>
</tr>
</tbody>
</table>
Chapter 4: Manuscript 3

4.8 References


Chapter 4: Manuscript 3


Context of Manuscript in Relation to the Thesis

Scientific research has long endeavoured to understand the aspects of the fast bowling technique that contribute to lumbar spine injury, yet little research has focused on how to reduce the prevalence of lumbar spine injury in fast bowlers. The lack of research may be attributed to the limited avenues for intervention that includes bowling workload restriction and/or technique modification. Governing bodies and administrators tend to implement bowling workload restrictions due to the relative ease and cost effectiveness of this type of intervention. Nevertheless, there are conflicting reports on how successful limiting bowling workload is on reducing injury risk in junior fast bowlers. Although more labour intensive, coaching programs focused on altering bowling technique have been shown to be effective in reducing known risk factors such as the mixed action and shoulder counter-rotation, there is limited research on their effectiveness to reduce injury risk in junior fast bowlers. The previous manuscripts in this thesis have shown that the mixed action is highly prevalent among junior fast bowlers (Manuscript 1). While shoulder counter-rotation was not linked to lumbar spine injury in Manuscript 2, previous research has shown that increased shoulder counter-rotation is related not only to injury but also decreased bowling accuracy when fatigued. Therefore, it is the aim of this manuscript to conclude this thesis with the examination of a structured coaching intervention aimed to reduce critical risk factors associated with lumbar spine injury in junior fast bowlers.
Chapter 5   A proposed coaching model for the reduction of lumbar injury risk in fast bowling

This chapter is an amended version of the manuscript: Schaefer, A., Ferdinands, R.E.D., O’ Dwyer, N., & Edwards, S. A proposed coaching model for the reduction of lumbar injury risk in fast bowling. To be submitted to the Journal of Sports Sciences.

5.1 Abstract

Background: Fast bowlers increased risk of lumbar injury has been cited to be associated with bowling technical factors that include the mixed bowling action, shoulder counter-rotation, front-limb knee extension and trunk lateral flexion. Strategies to reduce injury risk in junior bowlers have included bowling workload restrictions and/or coaching interventions, with the latter being shown to reduce known injury risk factors of fast bowling technique.

Aim: To determine whether a randomised-controlled seven-week coaching model would alter technical characteristics of the junior fast bowling technique that have been previously associated with lumbar spine injury.

Methods: Three-dimensional (3D) kinematic and kinetic data for the rear-limb, front-limb, trunk and bowling arm during the fast bowling action were collected from 21 male junior fast bowlers during a five-over spell at match pace. Participants were randomly assigned to the coaching (n = 11) and control (n = 10) groups, with the coaching group then completing a seven-week coaching intervention. Effectiveness of the coaching intervention was assessed with a mix-design factorial analyses of variance and individual case-study analyses.

Results: The control group displayed increased T12-L1 lateral flexion and rotation at bowling upper arm-vertical and reduced T12-L1 rotational range of motion during the
back-foot contact phase, and increased peak vertical ground reaction force loading rate compared to the coaching group. Examination of the individual cases saw improvements in all participants in the coaching group for at least one key variable, an overall 45% greater improvement in key bowling variables over the control group.

Conclusions: Improvement in both groups were observed after seven weeks of pre-season training, however the junior bowlers who undertook the specialised coaching intervention had a 45% greater improvement in their technique compared to those who did not participate in this intervention. This improvement in bowling technique would theoretically be beneficial to reducing lumbar spine injury risk in these at risk youth athletes. Therefore, coaching interventions modify key risk factors of the fast bowling technique should continue to be a key focus of reducing the risk of lumbar injury in junior fast bowlers.

5.2 Introduction
It is well established that cricketers have a higher risk of sustaining a lumbar spine injury during fast bowling compared to batting and fielding (Stretch, 2003) and the prevalence of this injury has been shown to be high for both senior (53%) and junior (24%) bowlers (Dennis, Finch, & Farhart, 2005; Elliott & Khangure, 2002; Stretch, 2003). Fast bowlers suffer a variety of overuse spinal injuries including spondylolysis, spondylolisthesis, pedicle sclerosis, intervertebral disc degeneration and stress fractures (Elliott, Hardcastle, Burnett, & Foster, 1992; Foster, John, Elliott, Ackland, & Fitch, 1989; Glazier, 2010; Portus, Mason, Elliott, Pfitzner, & Done, 2004).

Lumbar spine injury in fast bowlers has often been attributed to bowling technique (Portus et al., 2004). The four main fast bowling techniques are side-on, front-on, semi-open and mixed, and it is the mixed action that may increase the injury risk to the lumbar spine (Elliott, 2000). The concern for coaches and administrators is that the mixed action is very common within the bowling population - 44% to 80% of junior and senior bowlers use this action (Burnett, Elliott, & Marshall, 1995; Elliott &
The mixed action is typically characterised by excessive shoulder counter-rotation compared to the other three actions (Ferdinands, Kersting, et al., 2010; Portus et al., 2004). Shoulder counter-rotation greater than 30° (Foster et al., 1989) and 40° (Portus et al., 2004) has been reported to increase lumbar spine injury risk.

Greater shoulder counter-rotation, trunk and pelvic rotation has been shown to result in greater lumbo-pelvic loading in junior and adult bowlers (Crewe, Campbell, Elliott, & Alderson, 2013; Ferdinands, Kersting, & Marshall, 2009). Junior fast bowlers have been shown to produce maximum lumbo-pelvic torques during fast bowling of 10.4 ± 5.3 Nm·kg⁻¹·m⁻¹, 10.1 ± 3.5 Nm·kg⁻¹·m⁻¹, and 12.4 ± 4.3 Nm·kg⁻¹·m⁻¹ for flexion, rotation and lateral flexion, respectively (Crewe et al., 2013). It has been shown that if the spine is subjected to higher loading, it can lead to increased risk of spinal injury (Drake, Aultman, McGill, & Callaghan, 2005; Shirazi-Adl, Ahmed, & Shrivastava, 1986).

Other aspects of the bowling action that have been linked to lumbar spine injury risk are trunk lateral flexion and shoulder-pelvis separation angle. Increased lateral trunk flexion (48.6 ± 5.7°) away from the bowling arm in adult fast bowlers has been associated with lower back pain (Stuelcken, Ferdinands, & Sinclair, 2010). Shoulder-pelvis separation is calculated as the difference between the shoulder and pelvis alignment angles (Ferdinands, Kersting, & Marshall, 2014a). This separation angle has been tenuously linked to soft tissue injuries in the lumbar spine in adult fast bowlers (Portus et al., 2004), but no separation angle threshold in fast bowlers has been set to establish when lumbar spine injury risk increases for adult nor junior fast bowlers.

Fast bowling injury risk has traditionally been related to two-dimensional factors such as shoulder counter-rotation, yet fast bowling is a complex multi-planar motion involving the trunk and pelvis. To understand the relationship between multi-planar movement of the trunk and pelvis, a measure of lumbar spine injury risk known as ‘crunch factor’ has been proposed (Glazier, 2010).
investigate spinal loads (Ferdinands, Kersting, & Marshall, 2014b), the crunch factor has been calculated as the product of simultaneous lateral bending and rotational angular velocities of a segment(s) (Glazier, 2010). In golf, during the phase from downswing of the golf club to ball impact, a higher magnitude of crunch factor have been correlated with increased L5-S1 compressive and shear forces (Ferdinands et al., 2014b; Morgan, Cook, Banks, Sugaya, & Moriya, 1999). The utility of the crunch factor analysis in spinal injuries has only recently been investigated in fast bowling, with initial findings indicating a potential relationship between increased thorax crunch factor and spinal injury in junior and senior bowlers (Portus, Elliott, Lloyd, Galloway, & Timms, 2017). However, the authors emphasised that high variability of the crunch factor within a relatively small cohort of players may have influenced the high variability observed (Portus et al., 2017).

To date, three studies have examined the effectiveness of coaching interventions on altering bowling technique to reduce injury risk in fast bowlers. Elliott and Khangure (2002) found that junior fast bowlers (13.4 yr) were successful in decreasing shoulder counter-rotation from $35 \pm 13^\circ$ to $21 \pm 9^\circ$, leading to a reduced number using a mixed bowling action (81% to 33%) over a four-year period. A limitation of this study was that no control group was employed, as the authors believed that the level of the lumbar disc degeneration continues to increase with age if no changes in shoulder counter-rotation are made (Elliott & Khangure, 2002), but it is unclear if this rate of change of disc degeneration is affected by changes in the magnitude of shoulder counter-rotation. Ranson, King, Burnett, Worthington, and Shine (2009) found similar results for senior bowlers (18.5 ± 2.3 yr) over a two-year period showing that these bowlers significant decreased in shoulder alignment (relative to horizontal plane) at back-foot contact ($243 \pm 19^\circ$ to $231 \pm 12^\circ$) and shoulder counter-rotation ($45 \pm 15^\circ$ to $34 \pm 12^\circ$). However, it is not known how these changes to their bowling action were made as the technique modification were the responsibility of each participant’s coach (Ranson et al., 2009). In another study, a harness that restricted shoulder counter-rotation,
Shoulder-pelvis separation and lateral trunk flexion during the delivery stride was administered to junior fast bowlers (13 yr) over an eight-week period (Wallis, Elliott, & Koh, 2002). The junior participants were able to decrease shoulder counter-rotation but there was no significant short-term effect once the harness was removed (Wallis et al., 2002).

A randomised controlled study would provide stronger confirmation that coaching interventions are effective in reducing technique factors during fast bowling linked to lumbar spine injury. Therefore, the purpose of this study was to determine whether a randomised-controlled seven-week coaching model would alter technical characteristics of the fast bowling technique in junior fast bowlers that have been previously associated with lumbar spine injury. The aim was to decrease lumbar spine injury risk through the reduction of technical variables that have been associated with injury. We hypothesised that the coaching intervention would reduce these risk factors associated with lumbar spine injury risk in a sample of junior fast bowlers.

5.3 Methods

5.3.1 Participants

From local district and zone (pre-state) level representative teams within New South Wales, 21 junior male fast bowlers between 13 and 16 years (mean age = 13.9 ± 0.9 yr, height = 1.75 ± 0.08 m, mass = 61.6 ± 9.6 kg) were recruited. The bowler were classified as ‘fast’ by the director of coaching for their district prior to testing. Participants were assessed as clear of lower back injury/pain by a physiotherapist. Each participant and their parent/guardians gave written informed consent prior to data collection and approval for all methods was obtained from the institution’s Human Research Ethics Committee (H-2015-0059).
5.3.2 Experimental Protocol

The height, body mass, and trunk and pelvis dimensions of the participant were measured, prior to being prepared for a static standing trial in the anatomical position. A standardised warm-up exercises was then performed (Bird & Stuart, 2012), followed by six practice deliveries to familiarise the participants to the laboratory environment. The five-over spell (30 deliveries) protocol was then performed by the participant, which took ~1 hour to complete.

On a track the same length of a standard cricket pitch (20.12 m), each participant bowled at match pace (self-paced, self-selected run-up distance from the crease line) and attempted to land the ball at a target 6-8 m from the stumps on the track at the batting end. Between each over a non-bowling period of ~4-5 mins was performed to replicate game conditions, where the participants completed activities according to Schaefer, O’Dwyer, Ferdinands, and Edwards (2018).

The three-dimensional (3D) data were recorded for every delivery (30 ball deliveries) in the five-over spell. The participants’ body motion was recorded (500 Hz) using a 15-camera motion capture system (Oqus 700+, Qualisys AB, Göteborg, Sweden). Passive reflective markers were placed on the head, torso, pelvis and on each of the lower and upper limbs (Figure 5-1) which included makers on the lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, the ribcage bilaterally at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker and the lumbar segment (five tracking markers) (Crewe et al., 2013; Schaefer et al., 2018). On the cricket ball, three markers were placed on the side of the ball in triangle arrangement. To reduce the risk of occluding markers, participants wore minimal clothing, bowling in shorts, socks and athletic shoes. Two multichannel force platforms (Type 9281CA and 9281EA, Kistler, Winterthur, Switzerland) were used to measure 3D ground reaction forces (GRFs).
Each force platform was embedded in the floor and connected to control units (Type 5606, Kistler, Winterthur, Switzerland).

![Passive reflective marker positions for lower and upper limbs, pelvis, torso and head. Static markers were used for the static trial and removed for dynamic trials (including L-R 1st metatarsal, L-R medial malleolus, L-R medial femoral epicondyle) (Schaefer et al., 2018, p.10).](image)

**Figure 5-1**

5.3.3 **Data Reduction**

All 30 deliveries were selected for the analysis for 3D kinematics and kinetics, which was performed using Visual3D software (Version 5, C-Motion, Germantown, MD). A low-pass filter (Butterworth digital, fourth-order zero-phase with $f_c = 18$ Hz) was used to filter all raw kinematic, ground reaction force (GRF), moment and centre of pressure data. Following this, the temporal stage of the front foot ground contact during the bowling action was defined and the individual joint kinematics and net internal joint moments and forces during this stage were calculated (Bisseling & Hof, 2006). Raw GRFs were low-pass filtered at 50 Hz (Butterworth digital, fourth-order zero-phase) before peak magnitudes and loading rates were calculated using a customised LabView program (LabView, 2010, National Instruments Corporation, Austin, USA).

The temporal variables of the bowling action were defined and confirmed by visual inspection of the kinematic and kinetic data, as described by Schaefer et al. (2017).
These variables included back-foot initial foot-ground contact (BIC), front-foot initial ground contact (FIC), time of the peak vertical GRF ($F_v$), bowling upper-arm horizontal backwards (AH), ball release (BR), bowling upper-arm vertically downwards (AV), and front foot alignment (Figure 5-2) (Schaefer et al., 2018). The back-foot contact phase is defined from BIC to FIC, whereas the front-foot contact phase is defined from FIC to AV. Segment alignment angles including pelvis alignment, pelvis counter-rotation, shoulder alignment, shoulder counter-rotation and shoulder-pelvis separation angle at the time of BIC and FIC were defined according to the protocol of Ferdinands, Kersting, et al. (2010).

![Figure 5-2](image)

Figure 5-2 Stages of the bowling action: back-foot initial foot-ground contact (BIC; A), front-foot initial ground contact (FIC; B), bowling upper-arm horizontal backwards (AH; C), ball release (BR; D), and bowling upper-arm vertically downwards (AV; E) (Schaefer, et al., 2017, p.3).

The segment masses and inertial properties of the foot, shank, thigh, upper arm, forearm, hand and head were defined according to procedures outlined in Schaefer et al. (2018), as were the Cartesian local coordinate system and the sequence of rotation.

To calculate the inter-segmental trunk-pelvis joint angles, an $x,y,z$ Cardan sequence of rotation was used, expressed as extension-flexion, right-left lateral flexion and left-right rotation.

5.3.4 Data Analysis

Joint ranges of motion (ROM) were calculated for L5-S1 (5th lumbar - 1st sacral vertebrae) and T12-L1 (12th thoracic - 1st lumbar vertebrae) between BIC-FIC and FIC-BR. The ROM was defined as the difference between peak maximum and minimum joint angle for each period was computed. To calculate ball speed, the distance the ball
travelled after five frames, starting one frame after ball-release was divided by the
time taken for the five frames. Peak GRFs variables were calculated during the front-
foot contact phase, as well as the loading rate (F_v1) which is the rate to reach peak
vertical GRF. The net internal joint forces and moments were estimated via inverse
dynamics during the front-foot contact phase. If the participant’s front-foot did not
wholly contact the force platforms (unsuccessful trials; pre intervention= 25.1 ± 16.1%,
post-intervention = 23.3 ± 17.6%), the resultant kinetic variables were excluded from
statistical analysis. L5-S1 and T12-L1 joint forces were expressed relative to body
weight (relative BW), with peak net internal joint moments normalised to body mass
multiplied by height (relative BM x height). As researchers often use the incorrect
assumption that GRF variables infer joint loading, both GRF and joint loading variables
were included within this analysis (Edwards, Steele, Purdam, Cook, & McGhee, 2014).

Classification of an individual’s fast bowling action as side-on, front-on, semi-open or
mixed (four primary categories) was carried out according to the protocol of
Ferdinands et al. (2014a). Four ‘crunch factors’ were calculated as shown in Table 5-1,
based on planar segment velocities of the pelvis and the thorax during the fast bowling
action. These multi-segment crunch factors were chosen because they have been
shown to relate to high lumbar loads and shear forces during sporting movements
(Ferdinands et al., 2014b).

Table 5-1  Definition of crunch factors calculated using angular velocities.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF1 (Trunk_{flex-ext}*Trunk_{lat flex})</td>
<td>Trunk flexion/extension multiplied by trunk left/right lateral flexion.</td>
</tr>
<tr>
<td>CF2 (Trunk_{flex-ext}*Pelvic_{rot})</td>
<td>Trunk flexion/extension multiplied by pelvis axial rotation.</td>
</tr>
<tr>
<td>CF3 (Trunk_{lat ext}*Pelvic_{rot})</td>
<td>Trunk left/right lateral flexion multiplied by pelvis axial rotation.</td>
</tr>
<tr>
<td>CF4 (Trunk_{flex-ext}*Trunk_{lat flex} Pelvic_{rot})</td>
<td>Trunk flexion/extension multiplied by trunk lateral/medial flexion multiplied by pelvis axial rotation.</td>
</tr>
</tbody>
</table>
5.3.5 Coaching Intervention Protocol

All participants were randomly assigned to either the control (n = 10) or coaching group (n = 11). One participant from each group was excluded from the study due to withdrawing from the study. Seven coaching sessions each of two hours duration were conducted over a seven-week period, with each session consisting of warm-up exercises, implementation of drills and a final summary of the aims of the session. The coaching program was designed and implemented by an experienced and accredited international level coach (R.E.D.F.) and assisted by an accredited level two cricket coach (A.S.). Verbal and visual feedback were provided individually to each participant on their bowling action. A series of drills were implemented to achieve the three coaching aims that were to:

I. reduce shoulder counter-rotation;
II. reduce the shoulder-pelvis separation angle; and
III. increase pelvis segment rotation about the front hip joint to reduce relative lumbar spine motion.

5.3.6 Statistical Analysis

Means and standard deviations were calculated for all variables for all overs. A series of mixed-design factorial analyses of variance (ANOVAs) were used to determine significant changes (P<0.05) in the means across all variables. Outcome variables were split into the following categories for the primary test of the effect of coaching intervention versus control: angles, alignment, trunk-pelvis angle, range of motion (ROM), joint velocity, ball speed, crunch factor, GRFs (including impulses, timing and loading rate), joint forces and joint moments. The factors for analyses were the participant groups (coaching v control group), the intervention (pre- v post-), the stages of the bowling action (encompassing the six critical time points of BIC, FIC, FV, AH, BR and AV), and the phase intervals of the bowling action (comprising BIC-FIC, FIC-AH, AH-BR, BR-AV for the peak joint velocities and BIC-FIC, FIC-BR, BR-AV, FV and SH-
PEL SEP for crunch factors). The final factor was the specific output variable for the analysis (e.g. angles, alignments, etc.). There were four factors for analyses of the joint angles (group*intervention*stage*angles), trunk-pelvis angles (group*intervention*stage*angles), joint velocities (group*intervention*phase*velocities), and crunch factors (group*intervention*phase*factors). There were three factors for analyses of the alignment angles (group*intervention*alignment), joint ROM (group*intervention*ROM), ball speed (group*intervention*ball speed), ground reaction force/loading rate (group*intervention*force), impulse (group*intervention*impulse), GRF timing (group*intervention*timing), joint forces (group*intervention*jointforce) and joint moments (group*intervention*moment). The group factor was independent, while all the other factors were repeated measures. Since the study was only concerned with differences between the control and coaching groups and changes associated with the coaching intervention, only the main effects and interactions involving these factors are reported here. Partial eta squared was utilised to calculate effect sizes for all interaction for the repeated measures ANOVAs. Effects sizes ($\eta^2_p$) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson, 2011).

When significant effects were found, Tukey post hoc tests were conducted to identify their precise locus. All ANOVAs were carried out using Statistica (v.13, StatSoft Inc., Tulsa, OK, USA). The data were first checked to ensure that they satisfied the assumptions of normality of distribution and sphericity and in cases of violations of the latter, multivariate ANOVA was used. Residuals were examined to test the assumption of constant variance and normality. Constant variance was satisfied and normality accepted. If the Tukey post hoc did not indicate a significant effect following a significant interaction of ANOVAs, univariate and independent $t$-tests were employed to assess which variable was responsible for the interaction and effect size analyses, respectively. Effects sizes (d) were defined as trivial (<0.2), small (0.2-0.49), moderate
(0.5-0.79), and large (>0.8) size (Cohen, 1988). Individual case-study analysis was undertaken for all bowlers, with two threshold levels (5° ≥ and 10° ≥) set to determine positive or negative changes between pre- and post-intervention results. Those who had a change of 10° ≥ were also included in the 5° ≥.

5.4 Results

5.4.1 Coaching Adherence, Action Classification and Ball Speed

Over the seven-session program of this study, an attendance rate of 79% was observed for this intervention. The distribution of action types between groups is shown in Table 5-2. No significant main effect for group (F1,19 = 1.9, P = 0.18, η²p = 0.0911) or intervention (F1,19 = 3.52, P = 0.08, η²p = 0.1563) was observed for ball speed nor any significant interaction for the group*intervention*ball speed interaction (F1,19 = 0.23, P = 0.64, 0.0119; Figure 5-3).

Table 5-2 Distribution of action types for the control and coaching groups. Percentage breakdown of total action types per group.

<table>
<thead>
<tr>
<th>Action</th>
<th>Control (n=10)</th>
<th>Coaching (n=11)</th>
<th>All (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Side-on</td>
<td>0</td>
<td>0</td>
<td>1 (9%)</td>
</tr>
<tr>
<td>Front-on</td>
<td>2 (20%)</td>
<td>1 (10%)</td>
<td>3 (27%)</td>
</tr>
<tr>
<td>Semi-open</td>
<td>1 (10%)</td>
<td>1 (10%)</td>
<td>3 (27%)</td>
</tr>
<tr>
<td>Mixed</td>
<td>7 (70%)</td>
<td>8 (80%)</td>
<td>4 (36%)</td>
</tr>
</tbody>
</table>
Figure 5-3 Mean ± standard error (SE) of ball speed for control and coaching groups.

5.4.2 Angles

Segment alignments showed no significant main effect for group ($F_{1,19} = 0.97$, $P = 0.34$, $\eta^2 = 0.0484$) or intervention ($F_{1,19} = 0.49$, $P = 0.49$, $\eta^2 = 0.025$) and post-hoc analysis of a significant group*intervention*align interaction ($F_{12,228} = 2.27$, $P = 0.01$, $\eta^2 = 0.1067$; Figure 5-4A) revealed no significant effects. Following univariate tests it was observed that there was an effect of shoulder counter-rotation ($P = 0.01$), with a large effect size between the control and coaching group at post-intervention ($d = 1.27$). Front-foot lower limb joint angles showed no main effect of group ($F_{1,19} = 0.06$, $P = 0.81$, $\eta^2 = 0.0031$) or intervention ($F_{1,19} = 0.003$, $P = 0.96$, $\eta^2 = 0.0001$), as well as no significant interaction for group*intervention*stage*angle ($F_{32,608} = 0.78$, $P = 0.8$, $\eta^2 = 0.0395$, see Appendix 7.10; Figure 7-5). For torso joint angles, no main effect was seen for group ($F_{1,19} = 0.01$, $P = 0.9$, $\eta^2 = 0.0007$) or intervention ($F_{1,19} = 1.41$, $P = 0.25$, $\eta^2 = 0.0692$) was observed, yet a significant interaction was observed for group*intervention*stage*angle ($F_{25,475} = 1.74$, $P = 0.02$, $\eta^2 = 0.0838$). For BIC-BR; see Appendix 7.10; Figure 7-6. Post-hoc analysis of the interaction indicated that over the
seven-week period that the control group displayed significantly greater left T12-L1 lateral flexion and significantly increased T12-L1 left rotation at AV compared to pre-intervention, which led both groups to display similar values at post testing, while no change in this variable was observed in the coaching group (Figure 5-4B). The results of back-foot lower limb angles and bowling arm angles are shown in Appendix 7.10 (Figure 7-4 & Table 7-2). Torso range of motion from BIC to FIC showed no main effect for group (F\(_{1,19} = 1.42, P = 0.25, \eta^2_p = 0.0695\)) or intervention (F\(_{1,19} = 2.66, P = 0.12, \eta^2_p = 0.1227\)) but a significant group*intervention*ROM interaction (F\(_{5,95} = 2.52, P = 0.03, \eta^2_p = 0.1171\); Figure 5-5A). Post-hoc analysis revealed similar T12-L1 rotational ROM during BIC-FIC before the intervention, whereas at post testing the control group increased their ROM in contrast to the decrease ROM observed in the coaching group. Torso range of motion from FIC to BR observed no significant main effect for group (F\(_{1,19} = 0.11, P = 0.75, \eta^2_p = 0.0055\)) but it was observed there was a significant effect of intervention (F\(_{1,19} = 8.97, P = 0.01, \eta^2_p = 0.3206\) with a greater mean ROM at post-intervention (16.8 ± 0.5°) compared to pre-intervention (15.5 ± 0.5°, P = 0.007). There was no significant interaction for group*intervention*ROM interaction (F\(_{5,95} = 0.57, P = 0.72, \eta^2_p = 0.0293\); Figure 5-5B).

Trunk-pelvis angle statistical analyses returned no main effect for group (F\(_{1,19} = 0.0001, P = 0.99, \eta^2_p = 0.0000\), intervention (F\(_{1,19} = 1.68, P = 0.2, \eta^2_p = 0.0812\) or group*intervention*stage*angle interaction (F\(_{10,190} = 0.73, P = 0.7, \eta^2_p = 0.0368\) see Appendix 7.10; Figure 7-7).
Figure 5-4  Mean (± SE) segment alignment angles (A) and values of six torso joint angles at AV (B) between control and coaching groups. The following rotations are positive: L5-S1 flexion, L5-S1 left lateral flexion, L5-S1 right rotation, T12-L1 flexion, T12-L1 left lateral flexion, T12-L1 right rotation.
Figure 5-5  Mean (± SE) torso range of motion from BIC to FIC (A) and FIC to BR (B) between control and coaching groups.
5.4.3 Velocities

No main effect was observed for torso velocities for group ($F_{1, 19} = 1.02, P = 0.33, \eta_p^2 = 0.051$) or intervention ($F_{1, 19} = 1.55, P = 0.23, \eta_p^2 = 0.0753$), nor any significant interaction for group*intervention*phase*velocities ($F_{33, 627} = 1.27, P = 0.14, \eta_p^2 = 0.0627$ see Appendix 7.10; Figure 7-8). There was also no effect of group ($F_{1, 19} = 2.07, P=0.19, \eta_p^2 = 0.0982$) or intervention ($F_{1, 19} = 0.09, P = 0.77, \eta_p^2 = 0.0046$) for crunch factor, nor for the interaction of group*intervention*phase*factors ($F_{12, 228} = 0.28, P = 0.99, \eta_p^2 = 0.0146$, see Appendix 7.10; Figure 7-9).

5.4.4 Kinetics during front-foot contact phase

A significant main effect of group was present for GRF and loading rate variables ($F_{1, 19} = 7.12, P = 0.02, \eta_p^2 = 0.2725$) with the control having greater overall mean GRFs and loading rate than the coaching group ($57.3 \pm 4.5$ v $40.6 \pm 4.3, P = 0.02$). There was no significant interaction of the intervention ($F_{1, 19} = 2.19, P = 0.16, \eta_p^2 = 0.1034$).

Significant outcomes of the group*intervention*force interaction ($F_{7, 133} = 2.61, P = 0.01, \eta_p^2 = 0.1207$; Figure 5-6A) showed with post-hoc analysis that not only did the control group have a higher loading rate pre- and post-intervention compared to the coaching group, they also significantly increased their loading rate over the seven-week period.

No main effect for group ($F_{1, 19} = 0.23, P = 0.64, \eta_p^2 = 0.0118$) was observed for impulse but there was a significant main effect of intervention ($F_{1, 19} = 11.84, P = 0.003, \eta_p^2 = 0.384$), with greater mean impulses at post- ($0.042 \pm 0.002$ BW) than pre-intervention ($0.038 \pm 0.002$ BW, $P = 0.003$). No significant interaction was present for group*intervention*impulse ($F_{4, 76} = 0.72, P = 0.58, \eta_p^2 = 0.0367$; Figure 5-6B). For timing of peak force, no main effect was observed for group ($F_{1, 19} = 0.07, P = 0.79, \eta_p^2 = 0.0038$) but a significant effect of intervention was seen ($F_{1, 19} = 15.8, P < 0.05, \eta_p^2 = 0.4541$) with a greater mean time to peak forces at post- ($0.039 \pm 0.001$ sec) than pre-intervention ($0.037 \pm 0.001$ sec, $P < 0.05$). There was no significant interaction of
group*intervention*timing (F_{7,133} = 0.24, P = 0.97, \eta_p^2 = 0.0127; Figure 5-6C). Torso joint
moments showed no effect for group (F_{1,19} = 1.18, P = 0.29, \eta_p^2 = 0.0585) but a significant
effect of intervention (F_{1,19} = 62.02, P < 0.05, \eta_p^2 = 0.7655) with greater mean moment
at post-intervention (6.05 ± 0.23 relative BM x height) than pre-intervention (4.06 ± 0.2 relative BM x height, P < 0.05). There was no significant
group*intervention*moment interaction for the torso (F_{11,209} = 0.6, P = 0.83, \eta_p^2 = 0.0305; Figure 5-7A) joint moments. For torso joint forces, the group interaction returned no
significant main effect of group (F_{1,19} = 0.29, P = 0.6, \eta_p^2 = 0.0149), intervention (F_{1,19} = 0.9, P = 0.36, \eta_p^2 = 0.0451) or pre/post*jtforce*group interaction (F_{6,114} = 0.45, P = 0.85, 
\eta_p^2 = 0.023; Figure 5-7B). Lower limb joint moments are shown in Appendix 7.10 (Figure 7-10).
Figure 5-6  Mean (± SE) of ground reaction forces and loading rate (A), impulses (B) and timing (C) between control and coaching groups.
Figure 5-7  Mean (± SE) of torso joint moments (A) and torso joint forces (B) between control and coaching groups.
5.4.5 Individual Case Data - Kinematics

The individual pre- and post- intervention data for key kinematic risk factors is located in Table 5·3 for the coaching group and Table 5-4 for the control group. The breakdown of positive and negative changes in the key kinematic risk factors for the coaching and control groups are presented in Table 5-5.
Table 5-3: Mean segment alignment angles, trunk angles, pelvis segment angles and ball speed of coaching group at pre- and post-intervention. Green highlights positive outcomes and red highlights negative outcomes.

<table>
<thead>
<tr>
<th>Bowler</th>
<th>Action Type</th>
<th>Time</th>
<th>Sh-pel at FV</th>
<th>pel sep</th>
<th>Peak pel sep</th>
<th>sh-rot</th>
<th>Sh counter-rot</th>
<th>Pel counter-rot</th>
<th>Max flex/ext</th>
<th>Max trunk flex</th>
<th>Max trunk lat flex</th>
<th>Pelvis segment angle</th>
<th>Ball Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Front-on</td>
<td>Pre</td>
<td>-18°</td>
<td>-21°</td>
<td>36°</td>
<td>22°</td>
<td>17°</td>
<td>-30°</td>
<td>-42°</td>
<td>1°</td>
<td>19°</td>
<td>88km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-14°</td>
<td>-17°</td>
<td>35°</td>
<td>21°</td>
<td>16°</td>
<td>-39°</td>
<td>-38°</td>
<td>4°</td>
<td>25°</td>
<td>91km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Mixed</td>
<td>Pre</td>
<td>-44°</td>
<td>-62°</td>
<td>47°</td>
<td>28°</td>
<td>-7°</td>
<td>-21°</td>
<td>-56°</td>
<td>27°</td>
<td>30°</td>
<td>92km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>39°</td>
<td>-52°</td>
<td>27°</td>
<td>26°</td>
<td>-3°</td>
<td>-26°</td>
<td>-65°</td>
<td>23°</td>
<td>20°</td>
<td>99km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Semi-open</td>
<td>Pre</td>
<td>-27°</td>
<td>-27°</td>
<td>19°</td>
<td>15°</td>
<td>17°</td>
<td>-41°</td>
<td>-54°</td>
<td>-14°</td>
<td>-13°</td>
<td>87km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-23°</td>
<td>-26°</td>
<td>17°</td>
<td>15°</td>
<td>7°</td>
<td>-41°</td>
<td>-59°</td>
<td>-17°</td>
<td>18°</td>
<td>92km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mixed</td>
<td>Pre</td>
<td>-23°</td>
<td>-27°</td>
<td>45°</td>
<td>33°</td>
<td>-25°</td>
<td>-32°</td>
<td>-27°</td>
<td>1°</td>
<td>9°</td>
<td>85km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-14°</td>
<td>-17°</td>
<td>42°</td>
<td>27°</td>
<td>-2°</td>
<td>-36°</td>
<td>-40°</td>
<td>0°</td>
<td>9°</td>
<td>84km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Front-on</td>
<td>Pre</td>
<td>-26°</td>
<td>-28°</td>
<td>25°</td>
<td>6°</td>
<td>-11°</td>
<td>-25°</td>
<td>-33°</td>
<td>28°</td>
<td>35°</td>
<td>88km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-24°</td>
<td>-25°</td>
<td>19°</td>
<td>4°</td>
<td>1°</td>
<td>-29°</td>
<td>-31°</td>
<td>21°</td>
<td>35°</td>
<td>89km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Mixed</td>
<td>Pre</td>
<td>-30°</td>
<td>-31°</td>
<td>42°</td>
<td>17°</td>
<td>12°</td>
<td>-20°</td>
<td>-30°</td>
<td>21°</td>
<td>23°</td>
<td>85km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-35°</td>
<td>-39°</td>
<td>41°</td>
<td>16°</td>
<td>0.5°</td>
<td>-17°</td>
<td>-26°</td>
<td>21°</td>
<td>15°</td>
<td>81km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Semi-open</td>
<td>Pre</td>
<td>-43°</td>
<td>-49°</td>
<td>30°</td>
<td>12°</td>
<td>-2°</td>
<td>-29°</td>
<td>-47°</td>
<td>-1°</td>
<td>27°</td>
<td>87km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-26°</td>
<td>-30°</td>
<td>30°</td>
<td>8°</td>
<td>4°</td>
<td>-30°</td>
<td>-45°</td>
<td>0°</td>
<td>26°</td>
<td>88km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Semi-open</td>
<td>Pre</td>
<td>-44°</td>
<td>-49°</td>
<td>30°</td>
<td>7°</td>
<td>8°</td>
<td>-22°</td>
<td>-56°</td>
<td>-2°</td>
<td>11°</td>
<td>90km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-37°</td>
<td>-44°</td>
<td>24°</td>
<td>8°</td>
<td>5°</td>
<td>-25°</td>
<td>-62°</td>
<td>-5°</td>
<td>6°</td>
<td>95km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Mixed</td>
<td>Pre</td>
<td>-24°</td>
<td>-37°</td>
<td>57°</td>
<td>27°</td>
<td>3°</td>
<td>-30°</td>
<td>-71°</td>
<td>-20°</td>
<td>-19°</td>
<td>86km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-39°</td>
<td>-29°</td>
<td>49°</td>
<td>31°</td>
<td>7°</td>
<td>-24°</td>
<td>-61°</td>
<td>-10°</td>
<td>-6°</td>
<td>89km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Side-on</td>
<td>Pre</td>
<td>-36°</td>
<td>-44°</td>
<td>15°</td>
<td>9°</td>
<td>11°</td>
<td>-36°</td>
<td>-52°</td>
<td>34°</td>
<td>40°</td>
<td>82km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-29°</td>
<td>-44°</td>
<td>16°</td>
<td>7°</td>
<td>20°</td>
<td>-40°</td>
<td>-62°</td>
<td>33°</td>
<td>40°</td>
<td>81km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Front-on</td>
<td>Pre</td>
<td>-30°</td>
<td>-35°</td>
<td>36°</td>
<td>15°</td>
<td>6°</td>
<td>-33°</td>
<td>-43°</td>
<td>2°</td>
<td>28°</td>
<td>84km·h⁻¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-28°</td>
<td>-34°</td>
<td>41°</td>
<td>16°</td>
<td>-0.5°</td>
<td>-28°</td>
<td>-42°</td>
<td>12°</td>
<td>33°</td>
<td>80km·h⁻¹</td>
<td></td>
</tr>
</tbody>
</table>
Table 5-4: Mean segment alignment angles, trunk angles, pelvis segment angles and ball speed of control group at pre- and post-intervention. Green highlights positive outcomes and red highlights negative outcomes.

<table>
<thead>
<tr>
<th>Bowler</th>
<th>Action Type</th>
<th>Time</th>
<th>Sh-pel at FV</th>
<th>Sh-pel sep</th>
<th>Peak sh-pel rot</th>
<th>Sh counter-rot</th>
<th>Pelvis counter-rot</th>
<th>Max trunk flex/ext</th>
<th>Max trunk lat flex</th>
<th>Pelvis segment angles</th>
<th>Ball Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mixed</td>
<td>Pre</td>
<td>-36°</td>
<td>-44°</td>
<td>51°</td>
<td>16°</td>
<td>13°</td>
<td>-31°</td>
<td>-37°</td>
<td>21°</td>
<td>36°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-37°</td>
<td>-40°</td>
<td>52°</td>
<td>17°</td>
<td>3°</td>
<td>-24°</td>
<td>-30°</td>
<td>26°</td>
<td>44°</td>
</tr>
<tr>
<td>2</td>
<td>Semi-open</td>
<td>Pre</td>
<td>-20°</td>
<td>-23°</td>
<td>16°</td>
<td>13°</td>
<td>6°</td>
<td>-26°</td>
<td>-53°</td>
<td>2°</td>
<td>21°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-34°</td>
<td>-39°</td>
<td>17°</td>
<td>10°</td>
<td>-1°</td>
<td>-27°</td>
<td>-46°</td>
<td>12°</td>
<td>24°</td>
</tr>
<tr>
<td>3</td>
<td>Mixed</td>
<td>Pre</td>
<td>-30°</td>
<td>-48°</td>
<td>45°</td>
<td>24°</td>
<td>24°</td>
<td>-31°</td>
<td>-54°</td>
<td>2°</td>
<td>16°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-34°</td>
<td>-54°</td>
<td>47°</td>
<td>24°</td>
<td>0.8°</td>
<td>-31°</td>
<td>-52°</td>
<td>-2°</td>
<td>24°</td>
</tr>
<tr>
<td>4</td>
<td>Mixed</td>
<td>Pre</td>
<td>-31°</td>
<td>-42°</td>
<td>43°</td>
<td>25°</td>
<td>0.4°</td>
<td>-31°</td>
<td>-63°</td>
<td>27°</td>
<td>22°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-32°</td>
<td>-27°</td>
<td>52°</td>
<td>20°</td>
<td>6°</td>
<td>-29°</td>
<td>-50°</td>
<td>34°</td>
<td>22°</td>
</tr>
<tr>
<td>5</td>
<td>Front-on</td>
<td>Pre</td>
<td>-41°</td>
<td>-47°</td>
<td>36°</td>
<td>14°</td>
<td>-6°</td>
<td>-26°</td>
<td>-31°</td>
<td>40°</td>
<td>53°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-37°</td>
<td>-31°</td>
<td>40°</td>
<td>15°</td>
<td>-12°</td>
<td>-28°</td>
<td>-34°</td>
<td>37°</td>
<td>54°</td>
</tr>
<tr>
<td>6</td>
<td>Mixed</td>
<td>Pre</td>
<td>-26°</td>
<td>-37°</td>
<td>54°</td>
<td>33°</td>
<td>0°</td>
<td>-35°</td>
<td>-64°</td>
<td>2°</td>
<td>14°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-29°</td>
<td>-35°</td>
<td>56°</td>
<td>36°</td>
<td>2°</td>
<td>-31°</td>
<td>-56°</td>
<td>6°</td>
<td>16°</td>
</tr>
<tr>
<td>7</td>
<td>Mixed</td>
<td>Pre</td>
<td>-34°</td>
<td>-44°</td>
<td>49°</td>
<td>26°</td>
<td>2°</td>
<td>-31°</td>
<td>-51°</td>
<td>10°</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-34°</td>
<td>-44°</td>
<td>49°</td>
<td>24°</td>
<td>1°</td>
<td>-28°</td>
<td>-51°</td>
<td>7°</td>
<td>24°</td>
</tr>
<tr>
<td>8</td>
<td>Mixed</td>
<td>Pre</td>
<td>-24°</td>
<td>-41°</td>
<td>43°</td>
<td>22°</td>
<td>-3°</td>
<td>-37°</td>
<td>-57°</td>
<td>-2°</td>
<td>5°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-24°</td>
<td>-45°</td>
<td>49°</td>
<td>23°</td>
<td>-4°</td>
<td>-34°</td>
<td>-56°</td>
<td>5°</td>
<td>16°</td>
</tr>
<tr>
<td>9</td>
<td>Mixed</td>
<td>Pre</td>
<td>-19°</td>
<td>-19°</td>
<td>51°</td>
<td>20°</td>
<td>0.5°</td>
<td>-29°</td>
<td>-35°</td>
<td>12°</td>
<td>37°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-22°</td>
<td>-23°</td>
<td>49°</td>
<td>19°</td>
<td>5°</td>
<td>-33°</td>
<td>-36°</td>
<td>12°</td>
<td>35°</td>
</tr>
<tr>
<td>10</td>
<td>Front-on</td>
<td>Pre</td>
<td>-42°</td>
<td>-48°</td>
<td>39°</td>
<td>14°</td>
<td>-1°</td>
<td>-16°</td>
<td>-30°</td>
<td>20°</td>
<td>41°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>-45°</td>
<td>-48°</td>
<td>39°</td>
<td>15°</td>
<td>9°</td>
<td>-32°</td>
<td>-26°</td>
<td>23°</td>
<td>42°</td>
</tr>
</tbody>
</table>
Table 5-5: Breakdown of positive and negative changes for the coaching and control groups according to the results shown in Table 5-3 and Table 5-4. The results are displayed as a number of participants (n) and as a percentage (%) per group.

<table>
<thead>
<tr>
<th>Group</th>
<th>Type of Change</th>
<th>Threshold</th>
<th>Sh-pel sep at FV</th>
<th>Peak sh-pel sep</th>
<th>Sh counter-rot</th>
<th>Pelvis counter-rot</th>
<th>Max trunk flex/ext</th>
<th>Max trunk lat flex</th>
<th>Pelvis segment angles</th>
<th>Ball Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaching</td>
<td>Positive</td>
<td>5° ≥</td>
<td>5 (45.5%)</td>
<td>4 (36.4%)</td>
<td>1 (9.1%)</td>
<td>5 (45.5%)</td>
<td>2 (18.2%)</td>
<td>0</td>
<td>2 (18.2%)</td>
<td>3 (27.3%)</td>
</tr>
<tr>
<td></td>
<td>10° ≥</td>
<td>1 (9.1%)</td>
<td>3 (27.3%)</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>4 (36.4%)</td>
<td>0</td>
<td>0</td>
<td>2 (18.2%)</td>
<td>1 (9.1%)</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>5° ≥</td>
<td>2 (18.2%)</td>
<td>2 (18.2%)</td>
<td>1 (9.1%)</td>
<td>2 (18.2%)</td>
<td>2 (18.2%)</td>
<td>0</td>
<td>2 (18.2%)</td>
<td>4 (36.4%)</td>
</tr>
<tr>
<td></td>
<td>10° ≥</td>
<td>1 (9.1%)</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>0</td>
</tr>
<tr>
<td>Control</td>
<td>Positive</td>
<td>5° ≥</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>3 (27.3%)</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>4 (36.4%)</td>
</tr>
<tr>
<td></td>
<td>10° ≥</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2 (18.2%)</td>
<td>0</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>1 (9.1%)</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>5° ≥</td>
<td>1 (9.1%)</td>
<td>3 (27.3%)</td>
<td>2 (18.2%)</td>
<td>0</td>
<td>4 (36.4%)</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>1 (9.1%)</td>
</tr>
<tr>
<td></td>
<td>10° ≥</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>0</td>
<td>0</td>
<td>1 (9.1%)</td>
<td>1 (9.15)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Shoulder-pelvis separation (Sh-pel sep), counter-rotation (counter-rot), peak vertical ground reaction force (FV), flexion/extension (flex/ext), lateral flexion (lat flex), maximum (max)
5.5 Discussion

Fast bowling technique is often related to an increased incidence of lumbar spine injury (Elliott, 2000), leading to coaches and researchers to investigate intervention strategies to reduce this injury risk. In this current study’s randomised-controlled coaching intervention study, we aimed to modify shoulder counter-rotation, shoulder-pelvis separation angle and increase pelvis segment rotation from ball release through the follow-through variables associated lumbar spine injury risk in junior fast bowlers.

Shoulder counter-rotation is often the most fundamental technical error in fast bowling linked with lumbar spine injury (Elliott, 2000; Portus et al., 2004). In this current study, although no differences were seen in shoulder counter-rotation following ANOVA analyses, the univariate analyses showed a difference in shoulder counter-rotation resulting in greater shoulder counter-rotation with a large effect size in the control group (45 ± 11°) than when compared to the coaching group at post-intervention (31 ± 11°, d = 1.27). While there was a difference in shoulder counter-rotation, this change was not enough to alter the distribution of mixed bowlers in the coaching group. Upon closer analysis of the individual data, four of the 11 (36.4%) coaching participants showed reductions in shoulder counter-rotation, with one participant decreasing by 20° (Table 5-3; participant 2: 47° v 27°) In contrast, no participants in the control group reduced their shoulder counter-rotation, with two participants increasing their shoulder counter-rotation by more than 5° degrees. Therefore, preliminary evidence from this current study supports the use of coaching intervention to reduce shoulder counter-rotation and warrants the need for the same coaching intervention to be repeated on a greater sample and include a strategy(s) to increase participant’s adherence to the program.

It was also the aim of this coaching intervention to reduce shoulder-pelvis separation angle. Although there was a lack of differences in the grouped data, examination of the individual data saw four coaching participants reduce their peak shoulder-pelvis separation angle by 5° degrees (36.4%), with three of those bowlers reducing their
peak separation angle by 10°. Yet, two participants increased their separation angle, one participant by more than 5° degrees and the other by more than 10°. In contrast, three participants in the control group increased their peak separation angle by more than 5° degrees, one being greater than 10°. Also, only one control participant improved their peak shoulder-pelvis separation angle by 5°. As per shoulder counter-rotation, initial results of this study support the role of coaching as an intervention strategy to reduce shoulder-pelvis separation angle, a bowling variable that has been linked previously to soft tissue injury in the lumbar spine (Portus et al., 2004). The decreased shoulder-pelvis separation angle in the coaching group could theoretically reduce the load placed on the lumbar spine (Ferdinands, Stuelcken, Greene, Sinclair, & Smith, 2010), and thus potentially reducing the risk of lumbar soft tissue injury in junior fast bowlers.

This current study’s intervention also attempted to increase pelvis segment rotation about the hip joint of the front-leg to reduce the relative lumbar joint motion, particularly during the phase from ball-release to follow-through in the fast bowling action. For the coaching group, three participants increased their pelvis rotation but five participants had deterioration in their pelvis rotation. Interestingly, the control group had five participants improve their pelvis rotation and only one participant decreased their pelvis rotation. This may suggest that junior fast bowlers have an inability to control their pelvis movement during the fast bowling action, particularly during the front-foot contact phase through to follow through.

The motion of the trunk has been shown to be influential in lumbar spine injury risk during fast bowling (Stuelcken et al., 2010). In this current study it was shown that the coaching group was able to maintain their amount of trunk lateral flexion resulting in no change in T12-L1 motion over the duration of the intervention. In comparison, the control group displayed significant changes in their T12-L1 lateral flexion and left rotation at AV (Figure 5-3B). It is unclear at this stage of the bowling action at AV if
this change in technique during the follow-through has a detrimental effect on lumbar spine injury risk in junior fast bowlers.

Closer inspection of the individual data showed that lateral trunk flexion was reduced in two participants in the coaching group and one participant in the control group. Therefore, these individuals may have reduced the risk of developing low back pain and lumbar spine injury by keeping the spine in a more neutral position during the fast bowling action. Simultaneously, there were increases in trunk lateral flexion in two coaching group participants and one control group participant over 10°. However, this may be of little consequence as it has been previously shown that trunk lateral flexion above 40° is required to contribute to lumbar spine injury (Stuelcken et al., 2010). Only one participant displayed trunk lateral flexion above 40° and they did not change this magnitude with coaching and therefore have not altered their relative risk of a lumbar spine injury as a result of their participation within the intervention.

Fast bowlers need to withstand the high loading of their lumbar spine in order to perform at a high level (Crewe et al., 2013; Ferdinands et al., 2009). The control group displayed significantly greater loading rate at pre-intervention compared to the coaching group, and continued to significantly increase their loading rate until post-intervention. Therefore, bowlers in the control group are potentially increasing their injury risk, as it has been shown that increased loading rate increases the strain on the lumbar spine (Wang, Parnianpour, Shirazi-Adl, & Engin, 2000). Yet, no between-group differences were observed in this current study in spinal loading, suggesting that bowlers in the control group are dissipating load further down the kinetic chain.

Limitations possibly influencing the outcomes of this current study included sample size, adherence to the coaching intervention, and the simulation of match conditions. This cohort was of a limited sample size, which was restricted by the age-specific and competition level demographics recruited for this study in a regional location. While participants were adequately informed of the coaching intervention program, there
was suboptimal attendance at the coaching program (mean 79%, range 57-100%; see Appendix 7.10; Table 3). This may have affected the participants’ ability to achieve the desired outcomes to modify their bowling action. While re-creation of game-like conditions was attempted, the pitch surface and the outdoor setting could not be fully duplicated as participants performed the bowling protocol indoors on a concrete pitch with athletic shoes.

5.6 Conclusions
The results of this intervention have shown that a structured fast bowling coaching program can alter fast bowling technique in junior fast bowlers to reduce some of the risk factors associated with lumbar spine injury. While there were no significant between-group results, individual case analysis showed that some participants in the coaching group were able to improve certain biomechanical variables during the fast bowling action including shoulder counter-rotation (36%), shoulder-pelvis separation angle (46%) and trunk lateral flexion (18%). Even though some of the control group did show positive changes in technique over this period, the coaching group demonstrated more positive changes at 5° (45%) and at 10° (33%) than the control group emphasising that a specialised fast bowling coaching program is beneficial to reducing lumbar spine injury risk in youth fast bowlers. Therefore, further research with better adherence and a longer coaching program is required to counter the effects of non-responders and determine if the current protocol can significantly reduce lumbar injury risk.

5.7 Acknowledgements
The authors of this study acknowledge Professor Robert Robergs for his assistance with the LabView software to analyse ground reaction force data, Cricket NSW for assistance in recruiting participants and Wyong City Council and Tumbi Umbi Indoor sports for providing facilities to complete the coaching intervention. It should also be disclosed that funding was provided by iCare NSW to complete this study.
INFORMATION BOX

What is already known on this topic?
- Fast bowling is a highly stressful action resulting in high lumbar spine injury incidence for junior athletes.
- Factors previously related to lumbar spine injury risk during fast bowling include using a mixed bowling action, increased shoulder counter-rotation, trunk lateral flexion and front-knee extension.
- Previous investigations have shown that is possible to reduce shoulder counter-rotation through a fast bowling coaching intervention, however, change in other risk factors has been less effective.

What this study adds?
- Participants who responded to this fast bowling coaching intervention were able to improve their fast bowling technique, through reduced shoulder counter-rotation, shoulder-pelvis separation angle and trunk motion.
- When assessed on an individual basis, participants in the coaching group were able to make 45% more positive changes of greater than 5° or 33% more positive changes of greater than 10° than participants in the control group.
5.8 References


Chapter 6: Summaries & Conclusions

Chapter 6  Summary, Conclusions and Recommendation for Future Research

6.1 Summary of the Results
Fast bowling is a high impact activity resulting in high loads upon the body, particularly the lumbar region, leading to a high prevalence of lumbar spine injuries to fast bowlers. Current research has pointed to bowling workload and technique as potential key risk factors for lumbar spine injury in fast bowlers. In terms of technique, factors such as the mixed bowling action, shoulder counter-rotation, trunk lateral flexion and front-knee extension have all been identified as potential mechanisms that increase the risk of lumbar spine injury. While excessive shoulder counter-rotation in the mixed action is continually linked to increased injury risk, an accepted threshold of counter-rotation has not been agreed upon within the literature. Similarly, definitive evidence has not been provided to substantiate the biomechanical links between other aspects of fast bowling technique and injury. Due to their increased risk of injury, research has been conducted into interventions for fast bowlers, ranging from bowling coaching studies and implementation of a harness. These interventions were successful in reducing shoulder counter-rotation but did not change other aspects of bowling technique that has also been linked to lumbar injury. The research conducted into coaching interventions thus far is limited, as these studies were not randomised-controlled trial studies, hence questioning the validity of their results.

The aims of the current study were to: a) determine if there were any significant differences between action type mechanics in junior fast bowlers; b) determine the key biomechanical risk factors during junior fast bowling related to lumbar spine abnormalities (LSAs); c) investigate the relationship between lumbar spine loading and abnormalities with multi-segment crunch factor analyses and magnitude of crunch factor variability of the junior fast bowling action; and d) determine whether a randomised-controlled seven-week coaching model would alter technical
Chapter 6: Summaries & Conclusions

characteristics of the junior fast bowling technique that have been previously associated with lumbar spine injury. It was hypothesised respectively that: a) junior fast bowlers with different action types would employ kinematic and kinetic strategies that may be linked with injury risk, b) asymptomatic junior fast bowlers with LSAs would demonstrate greater shoulder counter-rotation, shoulder-pelvis separation angle, trunk lateral flexion, front knee extension and lumbar loading than those without an LSA, c) crunch factor would be positively correlated with spinal joint moments and forces and that junior fast bowlers with a LSA would present with greater crunch factor and low crunch factor variability, and d) the coaching intervention would reduce fast bowling risk factors associated with lumbar spine injury risk in junior fast bowlers. To achieve this thesis aim a), 60 male junior fast bowlers were recruited from metropolitan and rural representative team across two cohorts, while for aims b)–d), 23 male junior fast bowlers were recruited from metropolitan and rural representative teams.

The results supported some of this thesis hypotheses, while opposing others, and providing new avenues for investigation for lumbar spine injury risk in junior fast bowlers. The results of this thesis supported the hypothesis that a) in that the mixed action displayed greater segment alignment, and trunk and lumbar movement during back-foot ground contact but did not show increased lumbar loading during front-foot ground contact. The lack of differences in kinetics during front-foot contact between action types suggests that fast bowlers use similar kinematic patterns during front-foot contact.

The thesis results did not support the hypothesis b) because bowlers with a LSA did not display greater shoulder counter-rotation, shoulder-pelvis separation angle, trunk lateral flexion or lumbar loading during the fast bowling action. The results did however support the thesis hypothesis that a more extended front-knee is linked to LSA, along with greater front-hip internal rotation and restricted T12-L1 rotational range of motion during back-foot ground contact during the bowling. This indicates
that traditional factors associated with lumbar spine injury during the fast bowling action may not be as influential as previously thought.

The results of multi-segment crunch factor analysis of the fast bowling technique did not support the thesis hypothesis c), with no differences in crunch factors observed between control and LSA groups. Nevertheless, certain crunch factor combinations during the bowling action were correlated with increased spinal lateral shear joint force and decreased compressive joint force, hence potentially influencing injury risk. Therefore, further investigation in a larger cohort into the crunch factor appears justified to provide more definitive results.

For the thesis hypothesis d), the results did not support the notion that a bowling coaching intervention could reduce the biomechanical factors associated with lumbar spine injury in junior fast bowlers. Inspection of individual data, however, indicated possible responders and non-responders to the bowling intervention, implying that coaching may still be a viable option within junior fast bowlers to reduce their lumbar spine injury risk. Further investigation of the bowling coaching approach to reduce injury risk in these developing youth athletes appears warranted.

The results of these studies within this thesis provide a comprehensive analysis of biomechanical differences action types, biomechanical risk factors associated with lumbar spine injury, effect of multi-segment crunch factor on lumbar spine injury and the effectiveness of coaching intervention on technique modification in the fast bowling action. In line with previous research, the results of this study found that of the four main action types, the majority of the junior fast bowlers adopt a mixed bowling action (43%), placing them at a high risk of lumbar spine injury. The main differences in action types were seen in the kinematics during back-foot ground contact, including greater shoulder alignment, shoulder counter-rotation, T12-L1 left rotation, T12-L1 rotational range of motion and trunk left rotation during the fast bowling action. The only differences seen during front-foot ground contact was greater
right trunk rotation in front-on bowlers compared to mixed and semi-open bowlers at ball release and at the point of the bowling upper-arm being vertically downwards, while the semi-open bowlers had significantly lower loading rate than front-on and mixed action bowlers. The lack of kinematic differences at the front-foot contact phase may explain why there were no differences observed in the peak spinal joint moments nor forces during this phase of the bowling action, suggesting that junior fast bowlers of all action types use similar movement strategies after the point of front-foot ground impact. Since the majority of kinematic differences between action types occurred during back-foot ground contact, further investigation is therefore needed on back-foot lumbar loading in the different action types in junior fast bowlers.

When assessing biomechanical differences in asymptomatic junior fast bowlers with LSAs, the results of this study are in opposition to previous research that suggested that excessive shoulder counter-rotation is linked to increased lumbar spine injury. No differences in shoulder counter-rotation or trunk lateral flexion were seen here between bowlers who were uninjured and those with LSAs. Rather, those asymptomatic bowlers who presented with a LSA had greater knee extension at ball release, greater hip internal rotation at the point where the bowling upper-arm is horizontal backwards, and less T12L1 rotational range of motion. While this might suggest that asymptomatic bowlers with a LSA are less able than those without injury to dissipate vertical ground reaction forces, no differences in lumbar loading were actually seen between LSA and non-injured bowlers during the front-foot contact phase. The restricted range of motion of T12L1 in the axial plane during the fast bowling action could potentially increase the strain on the lumbar spine, and this again points to the need to measure back-foot kinetics.

While single segment crunch factor analysis has been utilised in fast bowling research, this thesis was the first to investigate the relationship between fast bowling LSAs and multi-segment crunch factors. The use of crunch factor analysis was proposed as a method of measuring the relationships in the motion of segmental multi-planar
movements such as fast bowling and golf. While the product of trunk flexion/extension and pelvis rotation was a predictor of spinal lateral shear joint forces during the fast bowling action, there were no differences between bowlers with and without a LSA, nor were there any differences in the magnitude of the crunch factor variability. The lack of significant findings in the crunch factor may be due to high variability within the crunch factor variables, as the multiplication of angular velocities increases the amount of noise present within the variable. Alternatively, the calculation of crunch factor by utilising angular displacement may be used to reduce noise within the crunch factor or alternately the coordination variability of the trunk and pelvis segments during fast bowling to describe the relationship between these segments and injury risk should be examined.

Previous research has shown that shoulder counter-rotation can be reduced through coaching interventions, but the lack of control groups in these previous studies may undermine these studies findings. This thesis was the first to provide a randomised controlled trial study of a bowling coaching intervention. While the grouped data did not yield significant changes in the key injury mechanisms during the fast bowling action, the examination of the individual participant data found that a junior fast bowler may be either a responder or non-responder to the coaching intervention, as there were both positive and negative changes in both groups. Certain participants in the coaching group were able to make more positive changes (45%) in their fast bowling technique based on the variables analysed in this thesis compared to participants in the control group. There were also 33% more positive changes in the coaching group than the non-coaching group when the threshold for change was set at a higher level. Potential injury mechanisms during the fast bowling action that were improved comprised of shoulder counter-rotation, shoulder-pelvis separation angle and trunk motion. Reasons that non-responders to the bowling intervention may have been less successful in changing their bowling technique may include lack of attendance, difficulty in following coaching instructions or not enough time to adapt to change to
the technique modifications. This may mean that coaching of the bowling technique cannot be ruled out as an effective means of reducing bowling risk factors associated with lumbar spine injury. Factors to consider in order to reduce the number of non-responders in a coaching group include the length of the intervention, the duration of the session, the type of feedback given and type of practice given to maximise changes in technique in youth fast bowlers.

6.2 Conclusions

The high rates of lumbar spine injury among junior and adult fast bowlers have led to increased research to understand the mechanisms of injury and how to decrease the injury risk in these athletes. These studies within this thesis have attempted to better understand the differences in fast bowling action types, potential biomechanical factors associated with asymptomatic bowlers with a lumbar spine abnormality and the effectiveness of a structured coaching intervention on reducing biomechanical factors associated with lumbar spine injury in junior fast bowlers. The primary differences in bowling action types appear to occur during back-foot contact phase, with few differences seen during front-foot contact phase. This outcome may be a result of the methods used to classify action types and suggests a need to redefine by building upon current classifications of action types to identify further differences between bowling actions. In terms of lumbar spine injury risk, traditional biomechanical factors identified to increase risk such as shoulder counter-rotation and trunk lateral flexion were not found to be significant. Rather, front-leg mechanics and restricted lumbar rotational motion during back-foot contact in the bowling action were found to be linked to lumbar spine abnormalities, suggesting that asymptomatic bowlers with a lumbar spine abnormality may not be as well-equipped as non-injured bowlers to absorb the load during the bowling action. The crunch factor analysis of the fast bowling action suggested that the movement of the trunk and pelvis may impact lateral shear joint forces, but a more substantial sample size is needed to link crunch factors with lumbar spine injury risk. To combat the injury risk, a coaching intervention
was employed and those who responded positively to the bowling intervention appeared to be able to reduce biomechanical risk factors associated with injury. Therefore, the use of coaching shows potential as a method of reducing the lumbar spine injury incidence in junior fast bowlers.

6.3 Recommendations for Future Research
Following are recommendations for future research based on the findings of the current studies:

a) Examine a more comprehensive sample of the fast bowling population that includes more side-on fast bowlers, in order to determine whether there are significant differences in the side-on action compared to the other three action types;

b) Analyse spinal joint kinetics during back-foot phase rather than just the front-foot ground contact phase when comparing action types, so as to establish whether differences in kinematics during back-foot ground contact phase result in increased lumbar injury risk in fast bowlers;

c) Investigate lumbo-pelvic and trunk movement in relation to the restricted movement of the lumbar spine and the effect on lumbar loading during fast bowling;

d) Investigate the role of the front lower limb and its association with absorbing ground reaction forces during front-foot ground contact in the fast bowling action leading to lumbar spine injury;

e) Analyse crunch factor variables during the fast bowling action on a larger sample size to definitively establish their role in injury risk on lumbar spine in fast bowling;

f) Investigate if crunch factors during the fast bowling action are related to greater lumbar loading or whether fast bowling action types influence the magnitude of crunch factors;
Chapter 6: Summaries & Conclusions

g) Investigate a potential role of coordination variability and during the fast bowling action in order to determine whether a reduction in degrees of freedom leads to an increased lumbar spine injury risk in fast bowlers; and

h) Carry out a randomised controlled trial of a longer coaching intervention program with a larger sample size in order to effectively prove that coaching can reduce the technique risk factors associated with lumbar spine injury.
Chapter 7 Appendices
Appendix 7.1

7.1 Ethical Clearance

12 September 2014

Mr Andrew Schaefer
School of Human Movement Studies
Charles Sturt University
Panorama Avenue
BATHURS NSW 2795

Dear Mr Schaefer,

Thank you for the additional information forwarded in response to a request from the Human Research Ethics Committee (HREC).

The CSU HREC reviews projects in accordance with the National Health and Medical Research Council’s National Statement on Ethical Conduct in Research Involving Humans.

I am pleased to advise that your project entitled “Investigation into injury mechanisms associated with junior fast bowling across a season” meets the requirements of the National Statement; and ethical approval for this research is granted for a twelve-month period from 12 September 2014.

The protocol number issued with respect to this project is 2014/169. Please be sure to quote this number when responding to any request made by the Committee.

Please note the following conditions of approval:

- all Consent Forms and Information Sheets are to be printed on Charles Sturt University letterhead. Students should liaise with their Supervisor to arrange to have these documents printed;
- you must notify the Committee immediately in writing should your research differ in any way from that proposed. Forms are available at: http://www.cau.edu.au/ data/assets/word_doc/0012/963768/Report-on- Research-Project_20130503.doc (please copy and paste the address into your browser);
- you must notify the Committee immediately if any serious and or unexpected adverse events or outcomes occur associated with your research, that might affect the participants and therefore ethical acceptability of the project. An Adverse Incident form is available from the website; as above;
- amendments to the research design must be reviewed and approved by the Human Research Ethics Committee before commencement. Forms are available at the website above;

www.csu.edu.au

Last updated: February 2014
Next review: February 2015
If an extension of the approval period is required, a request must be submitted to the Human Research Ethics Committee. Forms are available at the website above;

- you are required to complete a Progress Report form, which can be downloaded as above, by 14 August 2015 if your research has not been completed by that date;
- you are required to submit a final report, the form is available from the website above.

YOU ARE REMINDED THAT AN APPROVAL LETTER FROM THE CSU HREC CONSTITUTES ETHICAL APPROVAL ONLY.

If your research involves the use of radiation, biological materials, chemicals or animals a separate approval is required from the appropriate University Committee.

The Committee wishes you well in your research and please do not hesitate to contact the Executive Officer on telephone (02) 6338 4628 or email ethics@csu.edu.au if you have any enquiries.

Yours sincerely

Julie Hicks
Executive Officer
Human Research Ethics Committee
Direct Telephone: (02) 6338 4628
Email: ethics@csu.edu.au
Cc: Dr Neil Edwards, Associate Professor Nicholas O’Dwyer

This HREC is constituted and operates in accordance with the National Health and Medical Research Council’s (NHMRC) National Statement on Ethical Conduct in Human Research (2007)
Appendix 7.1

HUMAN RESEARCH ETHICS COMMITTEE

Acknowledgement of Receipt of Submission

To Chief Investigator or Project Supervisor:  Doctor Suzi Edwards
Cc Co-investigators / Research Students:  Dr Edouard Ferdinands
                                               Mr Andrew Schaefer
Re Protocol:  Investigation into injury mechanisms associated with
                                      Junior fast bowling across a season (2)
Date:  02-Jul-2016
Reference No:  H-2016-0068

Thank you for your Response to Conditional Approval (minor amendments) submission to the Human Research Ethics Committee (HREC).

Your submission will be considered under Expedited review by the Ethios Administrator at the earliest opportunity and you will be advised of the outcome.

Your protocol reference number is H-2016-0068. Please use this in any correspondence with the HREC in relation to this protocol.

Enquiries regarding progress with this submission can be directed to Human-Ethics@newcastle.edu.au or 492 17894.

For advice on ethical conduct in human research please refer to a Research Ethics Advisor in your Faculty. Details are available from the Human Research Ethics website.

Human Research Ethios Administration

Research Services
Research Integrity Unit
The Chancellery
The University of Newcastle
Callaghan NSW 2308
T +61 2 492 17894
F +61 2 492 17164
Human-Ethics@newcastle.edu.au

RIMS website - https://RIMS.newcastle.edu.au/ethics

Linked University of Newcastle administered funding:

<table>
<thead>
<tr>
<th>Funding body</th>
<th>Funding project title</th>
<th>First named Investigator</th>
<th>Grant Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>WorkCover Authority of New South Wales/WorkCover Sports Research and Injury Prevention (°)</td>
<td>Correction of bowling technique for prevention of lumbar injury in junior fast bowlers</td>
<td>Edwards, Suzi</td>
<td>01401475</td>
</tr>
</tbody>
</table>

The[123456789]Newcastle%Ethics%Ethics%20Reply%BC%20Submission%20Acceptance.htm
Appendix 7.2

7.2 Information Sheet

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study, the Chief Investigators may be contacted at any time.

Andrew Schaefer (Principal Investigator) PhD Student
School of Human Movement Studies
Allen House, NIT
Faculty of Science
Charles Sturt University
Panorama Av., Bathurst, NSW 2795
Mob: 0457 244 259
Email: schaefer.89@gmail.com

Mihiri Kuruppu (Principal Supervisor)
School of Human Movement Studies
Allen House, NIT
Faculty of Science
Charles Sturt University
Panorama Av., Bathurst, NSW 2795
Mob: 0418 312 459
Email: mihiri.kuruppu@csu.edu.au

Allan Nicholas O’Flynn (Associate Supervisor)
School of Human Movement Studies
Allen House, NIT
Faculty of Science
Charles Sturt University
Panorama Av., Bathurst, NSW 2795
Mob: 0418 312 459
Email: oflynn.allan@csu.edu.au

Background Information

There has been an increasing concern surrounding the increase in lower back injury not only amongst elite fast bowlers but also in the junior players. Further investigation is needed to inform clinicians and coaches as to the best approach to reduce lumbar injury risk in fast bowlers. We plan to test the change of the bowling action of junior fast bowlers (13 to 16 years) from the beginning to the end of the season and its association with lumbar spine injury. With this information, more knowledgeable decisions can be made regarding the key factors associated with fast bowling injury.

Purpose

The aim of this study is to assess if there are any changes in fast bowling action and lumbar spine injury in junior fast bowlers over a single cricket season in a rural region. By monitoring the mechanics of the action at the beginning and completion of a season combined with magnetic resonance imaging (MRI) analysis, it is hoped to identify critical aspects of bowling technique that are associated with lumbar spine injury in junior fast bowlers. It will provide essential knowledge for identifying athletes at risk.

Participant Requirements

Study Design

This study involves two parts. Part 1 will involve every participant undergoing testing at the beginning (September-October 2014) and end of the 2014-5 cricket season (March-April 2015) as shown below. You must participate in all of these testing sessions, which will be free of cost to you. If you decide to participate, and then decide that you do not wish to undergo any of these sessions such as the MRI of your lumbar spine, you will not be able to participate in any other further sessions within this study. During the study, if you wish not to continue your participation, you have the right to withdraw your consent and discontinue participation in the study at any time, and your relationship with CSU will not be affected.

| PART 1 | 
| --- | --- |
| **Start of cricket season (September-October 2014)** | **End of cricket season (March-April 2015)** |
| Pre-testing questionnaires | Complete forms and email to Mr Andrew Schaefer |
| Physiotherapy assessment (~15 mins) | Charles Sturt University, Bathurst |
| MRI of lumbar spine, (~30 mins) | Bathurst |
| Biomechanical analysis of fast bowling technique (~3hrs) | Biomechanics Laboratory, Charles Sturt University, Bathurst |

www.csu.edu.au

CRICOS Provider Numbers for Charles Sturt University are 00009F (NSW), 010987 (Vic) and 03000B (ACT). ABN: 83 878 708 553

166
After you have read the Participant Information Package and had any of your questions answered, if you wish to proceed as a research participant you will be required to sign the Informed Consent Form and Parental Informed Consent Form, and complete an Injury History Questionnaire, Physical Activity Readiness Questionnaire (PAR-Q) and the Coronary Artery Disease Risk Factor Stratification form and submit these forms to Mr Schaefer. After sending these forms to Mr Schaefer, you will then be contacted by him and given details to arrange a (i) physiotherapist assessment that will ensure your suitability for inclusion into this study and if eligible to participate in this study, (ii) MRI of your lumbar spine at a time that is suitable to you. It should be noted that you will NOT be required to pay for any cost including the physiotherapy assessment or the MRI of your lumbar spine, this responsibility lies solely with Charles Sturt University and research grants. Mr Schaefer will also organise a time with you to undertake the biomechanical analysis of your fast bowling technique if you are eligible to participate in this study.

For Part 2 of this study, approximately 20 participants from who have been determined, on the basis of the critical risk factors identified in Part 1, as displaying the highest risk of lumbar injury will be selected. If you have been selected, you will be invited to participate in a 10-week pre-season specialised technical coaching intervention program (July-August 2015) during the pre-season of 2015-6 cricket season. You would be required to attend weekly specialised coaching sessions to modify your fast bowling technique to potentially reduced your injury risk and increase your performance. Following this you would undergo a second cricket season of biomechanical testing and lumbar spine MRI at both the beginning (September 2015) and end (April 2016) of a single junior cricket season, and monthly refresher specialised technical coaching sessions.

### PART 2

**Cricket pre-season specialised technical coaching intervention program (August 2015):**

<table>
<thead>
<tr>
<th>8 x coaching sessions (1 x 1-2 h/week)</th>
<th>Ballarat</th>
</tr>
</thead>
</table>

**Start of cricket season (September 2015):**

- MRI of lumbar spine, (~30 mins)
- Biomechanical analysis of fast bowling technique (~3 hrs)
  - Biomechanics Laboratory, Charles Sturt University, Ballarat

**During cricket season (2015-6):**

- Refresher coaching sessions (1 x 2 h/month)

**End of cricket season (April 2016):**

- MRI of lumbar spine, (~30 mins)
- Biomechanical analysis of fast bowling technique (~3 hrs)
  - Biomechanics Laboratory, Charles Sturt University, Ballarat

### Data Collection

**Physiotherapy assessment**

Prior to your participation in this study you will be required to undergo a physiotherapy assessment. This assessment will determine your eligibility to participate in this study, as those demonstrating current lower back injury/pain or other injury will be ineligible to participate within this study. This is due to the possibility of injury/pain altering your fast bowling technique. The assessment will take approximately 15 minutes and will be conducted by a qualified physiotherapist.

**Biomechanical analysis**

In order to analyse your bowling technique, it is essential that your bowling action be videoed for later analysis. All videos will remain completely confidential. Your bowling technique analysed over 5 overs using biomechanical analysis that involves special reflective markers and EMG (electromyography) detectors placed on the skin of both of your lower limbs, trunk and upper limbs. These markers will allow us to record your movement during the bowling action with special cameras. After completing a 10-minute warm-up of specific exercises, six practice balls at half pace will be performed to familiarise yourself with the process and the environment. You will then perform 5 consecutive six-ball overs at the pace you would naturally perform in a game situation from your naturally selected run up, with a 5-minute rest in between overs to replicate game situations. In your 5 min rest you will walk a distance of 5 metres every minute, with a basic fielding drill at random intervals to replicate the movements experienced during a match. There will be an area on the pitch that you will be required to aim for with each delivery to keep the action consistent. Your movements will be detected with the use of special markers on the skin. You will have the chance to practice the movements prior to data collection. Between each over you will have a 5 minute rest period in which you walk a distance of 5 metres every minute, with a basic fielding drill at random intervals to replicate the movements experienced during a game.

**MRI analysis**

To assess your level of lumbar spine injury you will be required to undergo MRI analysis at both the beginning and end of the cricket season(s). The MRI will take special pictures of your lumbar spine to assess the anatomy and

www.csu.edu.au

CPRCS Provider Numbers for Charles Sturt University are 000005 (NSW), 01947G (Vic) and 02900B (ACT). ABN: 83 079 708 554
INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study, the chief investigator may be contacted at any time:

**Background Information**

There has been an increasing concern surrounding the increase in lower back injury not only amongst elite fast bowlers but also in the junior players. Further investigation is needed to inform clinicians and coaches as to the best approach to reduce lumbar injury risk in fast bowlers. We plan to test the change of the bowling action of junior fast bowlers (13 to 16 years) from the beginning to the end of the season and its association with lumbar spine injury. With this information more knowledgeable decisions can be made regarding the key factors associated with fast bowling injury.

**Purpose**

The aim of this study is to assess if there are any changes in fast bowling action and lumbar spine injury in junior fast bowlers over a single cricket season in a rural region. By monitoring the mechanics of the action at the beginning and completion of a season combined with magnetic resonance imaging (MRI) analysis, it is hoped to identify critical aspects of bowling technique that are associated with lumbar spine injury in junior fast bowlers. It will provide essential knowledge for identifying athletes at risk.

**Participant Eligibility**

In order for your child to qualify for this study, they must be a current male junior fast bowler between the ages of 13 to 16 years at the start of the study. To maintain a relatively equal skill level among all participants, your child must have been selected for a district level side or above. Finally, your child must not be experiencing any lower back pain or injury at the beginning of the study as this may be affecting your child’s fast bowling technique. Therefore, your child must undertake a physiotherapist assessment (at no cost to you) that will ensure your child’s suitability for inclusion to participate in this study.

As this study is conducted in 2 parts, your child will be eligible to participate in Part 1 but may not be eligible to participate in Part 2. All participants will be invited to participate in Part 2, which is a specialised coaching program during the cricket season. Children selected for Part 2 will be identified as having a fast bowling technique that lends itself to high lumbar spine injury risk. If your child has been identified for Part 2 of the study, you will be promptly contacted by phone or email. It should be known that if you do not wish for your child to be involved in Part 2, that your child is still eligible to continue their participation in Part 1 of the study.

**Participant Requirements**

**Study Design**

This study involves two parts. Part 1 will involve every participant undergoing testing during the off season (June - July 2015), at the beginning of the season (September – October 2015) and end of the 2015-16 cricket season (March-April 2016) as shown below. Your child must participate in ALL of these testing sessions, which will be free of cost to you. If your child decides to participate, and then decide that they do not wish to undergo any of these sessions,
As the MRI of their lumbar spine, your child will not be able to continue their participation in any further within this study. During the study, if you or your child wish to stop their participation, either of you can withdraw your consent at any time and your relationship with The University of Newcastle, Charles Sturt University or Cricket NSW will not be affected.

After you and your child have read the Participant Information Package and had any of your questions answered, if you wish for your child to proceed as a research participant you and your child will be required to sign the Informed Consent Form and Parental Informed Consent Form, and complete an Injury History Questionnaire, Physical Activity Readiness Questionnaire (PAR-Q) and the Coronary Artery Disease Risk Factor Stratification form and submit these forms to Mr Schaefer. After sending these forms to Mr Schaefer, you will then be contacted by him and given details to arrange a physiotherapist assessment that will ensure your child’s suitability for inclusion into this study. It should be noted that you will NOT be required to pay for any cost including the physiotherapy assessment, DXA or the MRI of your child’s lumbar spine, this responsibility lies solely with The University of Newcastle, Charles Sturt University and research grants. Mr Schaefer will also organise a time with you to undertake the biomechanical analysis of your child’s fast bowling technique and full body scan (Dual-energy X-ray absorptiometry, DXA) by a qualified technician to provide analysis of lean mass (muscle), fat mass and bone mineral density, if your child is eligible to participate in this study.

Based on the biomechanical analysis of fast bowling technique in the Pre-Season testing, your child may be one of approximately 20 participants who will be invited to participate in Part 2 coaching program. This intervention involves an 8-week pre-season specialised technical coaching intervention program (July-August 2015) during the pre-season of 2015-6 cricket season and refresher sessions during the cricket season that is led by an international cricket coach. Participants will be invited on the basis of the critical risk factors identified in their fast bowling technique, as displaying the highest risk of lumbar injury. In addition to Part 1 testing (white shaded area in table below), your child would also be required to attend weekly specialised coaching session during the pre-season and monthly refresher sessions during the cricket season (grey shaded area in table below highlight additional requirements) to modify your child’s fast bowling technique to potentially reduce your child’s injury risk and increase their performance.

Irrespective of whether your child is involved only in Part 1 or both Part 1 and 2, all participants will undergo one physiotherapy assessment, three dual-energy X-ray absorptions tests, two MRI of the lumbar spine, and three biomechanical analysis of their fast bowling technique, and complete weekly workload questionnaires during the cricket season outlined in the flow diagram below and the Tables on the following page.
Appendix 7.2

Requirements for participant involved in PART 1 ONLY.

**Pre-season (June-July 2015)**
- Pre-testing questionnaires
- Physiotherapy assessment (15 mins)
- Dual-energy X-ray absorptiometry (10 mins)
- Biomechanical analysis of fast bowling technique (3 hrs)

**Start of cricket season (September-October 2015)**
- MR of lumbar spine, (30 mins)
- Dual-energy X-ray absorptiometry (10 mins)
- Biomechanical analysis of fast bowling technique (3 hrs)
- The University of Newcastle, Currimbah

**End of cricket season (March-April 2016)**
- MR of lumbar spine, (30 mins)
- Dual-energy X-ray absorptiometry (10 mins)
- Biomechanical analysis of fast bowling technique (3 hrs)
- The University of Newcastle, Currimbah

Requirements for participant involved in PART 1 and 2.

**Pre-season (June-July 2015)**
- Pre-testing questionnaires
- Physiotherapy assessment (15 mins)
- Dual-energy X-ray absorptiometry (10 mins)
- Biomechanical analysis of fast bowling technique (3 hrs)

**8 x coaching sessions (1x2 hr/week)**
- The University of Newcastle, Currimbah

**Start of cricket season (September-October 2015)**
- MR of lumbar spine, (30 mins)
- Dual-energy X-ray absorptiometry (10 mins)
- Biomechanical analysis of fast bowling technique (3 hrs)
- The University of Newcastle, Currimbah

**During cricket season (2015-6)**
- Refresh coaching sessions (1x2 hr/month)
- The University of Newcastle, Currimbah

**End of cricket season (March-April 2016)**
- MR of lumbar spine, (30 mins)
- Dual-energy X-ray absorptiometry (10 mins)
- Biomechanical analysis of fast bowling technique (3 hrs)
- The University of Newcastle, Currimbah

Data Collection

**Physiotherapy assessment**

Prior to your child’s participation in this study, your child will be required to undergo a physiotherapy assessment. This assessment will determine your child’s eligibility to participate in this study, as those demonstrating current lower back injury/pain or other injury will be ineligible to participate within this study. This is due to the possibility of injury/pain altering your child’s fast bowling technique. The assessment will take approximately 15 minutes and will be conducted by a qualified physiotherapist.

**Biomechanical analysis**

In order to analyse your child’s bowling technique, it is essential that your child’s bowling action be videoed for later analysis. All videos will remain completely confidential. Your child’s bowling technique will be analysed over 5 overs using biomechanical analysis that involves special reflective markers placed on the skin of both of your child’s lower limbs, trunk and upper limbs. These markers will allow us to record your child’s movement during the bowling action with special cameras. After completing a 10-minute warm-up of specific exercises, six practice balls at half pace will be performed by your child to familiarise themselves with the process and the environment. Your child will then perform 5 consecutive six-ball overs at the pace they would naturally perform in a game situation from their naturally selected run up, with a 5-minute rest in between overs to replicate game situations. In the 5 min rest, your child will walk a distance of 5 metres every minute, with a basic fielding drill at random intervals to replicate the movements experienced during a match.
Dual-Energy X-ray Absorptiometry scanning

Dual-energy X-ray absorptiometry (DXA) scanning will be performed on three separate occasions during the experimental period. This information will allow us to determine your child’s lean mass (muscle), fat mass and bone mineral density. For DXA scanning, your child will lie down for approximately ten (10) minutes while a scanning arm will move above their body.

Dual-Energy X-ray Absorptiometry Scanning:
This research study involves exposure to a very small amount of radiation. As part of everyday living, everyone is exposed to naturally occurring background radiation and receives a dose of about 2,000 to 3,000 microsieverts (µSv) each year. The effective dose from this study is about 8 µSv (2.6 µSv per scan). At this dose level, no harmful effects of radiation have been demonstrated as any effect is too small to measure. The total effective dose from this study is below the 5,000 µSv total effective dose for participants up to the age of 18 years in research. Thus, according to the Australia Radiation Protection and Nuclear Safety Agency the level of risk in this project is considered negligible and is equivalent to Risk Category I (<1; 100,000).

Note: You should retain this information sheet for at least five years and provide to the Chief Investigators of future research projects involving exposure to ionising radiation that your child volunteers to participate in.

MRI analysis
To assess your child’s level of lumbar spine injury, your child will be required to undergo MRI analysis at both the beginning and end of the cricket season(s). The MRI will take special pictures of your child’s lumbar spine to assess the anatomy and function of this area that will be then assessed by a qualified radiologist. For further information regarding magnetic resonance imaging scans and what is involved visit the following websites:


Weekly Survey
During the cricket season(s) between each biomechanical testing your child will be required each week to complete and email two weekly surveys to Mr Schaefer. The first survey asks if your child experienced lower back pain during matches and training that week. While the second survey asks for information about how many hours of sport your child participated in, and number of deliveries bowled in cricket training and matches during that week. Each survey will be sent via email to the investigator Mr Schaefer. If your child sustains an injury at any point throughout the season, they will be required to fill out a separate survey outlining how they sustained the injury and how severe the injury is. This survey will also be sent to the investigator Mr Andrew Schaefer who will then contact you to discuss your child’s injury.

Coaching Intervention (Part 2 participants only)
Approximately 20 participants, selected on the basis of critical risk factors identified in Part 1 relating to highest risk of lumbar injury, will be invited to participate in a specialised coaching intervention program. This will be an 8-week program held in the 2015-16 cricket pre-season, and will be conducted by the world leading professional fast bowling coach and ex-first class cricketer Dr Edouard Ferdinands, and Level 2 cricket coach and investigator Mr Andrew Schaefer. Each session held during the pre-season will be 1-2 hours in length at a location to be confirmed. Monthly refresher sessions will then be held during the following season to maintain your child’s technique during the following cricket season. Each coaching session will involve your child performing a structured warm up of about 10-15 minutes, with the main body of the coaching session involving the training and modification of their fast bowling action with individualised feedback on aspects of key technical flaws within their bowling action that have been identified as a critical risk of lumbar injury. Training assistance devices that will assist in this technique modification may include cones, tape, swim noodles, elastic bands and hurdles. Core strengthening exercises may be employed to increase abdominal support, with the use equipment such as weighted gym balls and elastic bands. For feedback, slow motion video will be observed by the coaches and your child to display aspects of technique that are recommended to be improved. The coaches (Dr Ferdinands and Mr Schaefer) may also view these videos outside of the session to plan for the next week’s session.

Risks and Discomforts
As with all exercise there is the possibility of injury during the biomechanical testing. Such injuries that may occur during training or testing are primarily restricted to soft tissue injuries, such as muscle/tendon strains. All biomechanical and DXA testing will be performed at The University of Newcastle (Exercise Science Laboratory EXSB-101, Biomechanics Laboratory EXSB-212, Curtinbah campus). As such, the primary investigator (a trained first aider) will be available to provide assistance and telephones are readily accessible to contact emergency services if necessary.
necessary. To minimise the risk of injury, a thorough warm-up will be performed by your child before all training
sessions. In the event that an injury does occur from your child's participation in the study, any associated costs will
lie with you unless the injury was related solely to the negligence of The University of Newcastle or Charles Sturt
University. However, The University of Newcastle or CSU will assist where possible in obtaining appropriate medical
assistance. Participants will not be required to perform any movement with which they feel uncomfortable.

There is a possibility of musculoskeletal injury by performing such a long bout of exercise. Your child may experience
muscle soreness, joint inflammation, and/or muscle strains 24-48 hours after testing. These responses are common
and expected, and should subside within 5-7 days. The risks can be minimised by performing appropriate warm-up
and warm-down activities prior to and at the completion of testing.

MRI testing has been deemed a safe and effective method for diagnosis of sports injuries among adults, teenagers
and children alike, as low energy radio waves produce no radiation. However, there are some considerations to be
aware of when undergoing testing. The MRI testing procedure takes place within a confined space, therefore, those
who are uncomfortable with enclosed space may feel some discomfort and should inform the radiologist prior to
testing. To assist to keep the patient at ease a means of communication with the staff (such as a buzzer held by the
patient) can be used for contact if the patient cannot tolerate the scan. Also, metal objects or piercings may not be
worn during MRI testing as these are attracted by the high magnetic forces, causing some discomfort or pain and the
distortion of the final image. Therefore, all patients must remove any metal objects or piercings before taking the MRI
exam.

Benefits
Participation in this study will provide valuable assessment of the bowling action your child adopts and whether this is
increasing your child's risk of sustaining an injury to the lower back. This is of benefit as decreasing your risk of injury
will limit the time spent on the sidelines through injury. The assessment presented to your child at the end of the study
will provide them with any technical faults in their action that need to be corrected and of any lumbar spine injury they
may currently have including copies of the MRI reports.

Data Usage
It is anticipated that the data obtained from this study will result in scholarly research articles published in high-calibre
international sports science journals.

Confidentiality
The anonymity of participant's data will be protected and all data obtained from you will be kept strictly confidential.
Photos may be used in the research outcomes of this study and all participant's confidentiality will be protected in this
process through the blurring or covering of faces in order to protect the participants' identity.

Consent and Withdrawal
Permission for your child to be a participant in this study is entirely voluntary. You and your child have the right to
consent, or not to consent, to participate in this investigation. Should you decide for your child to participate or not,
your relationship with The University of Newcastle or Charles Sturt University will not be affected in any way. In
addition, if you decide to participate, you or your child have the right to withdraw your consent and discontinue
participation in the study at any time. Any decisions regarding participation will not affect any relationships with The
University of Newcastle, Charles Sturt University or Cricket NSW (including any team selection your child may pursue
in future sporting endeavours). If you or your child do decide to withdraw from this research project for any reason,
any data that may have already been collected may be still be utilised towards the final results, unless you request
your data be withdrawn within 3 months of being collected. If you or your child wish your child's data to be withdrawn,
any data and information specific to your child will be destroyed. If you as parent/guardian withdraw your consent,
your child will no longer be permitted to participate.

Liability
It is important to realise that all forms of medical or health science research, whether clinical or laboratory, involve
some risk of injury. In spite of all precautions, your child might be injured as a result of their participation in this study.
If physical injury does result from this investigation, the investigators will assist you in obtaining appropriate medical
your consent, your child will no longer be permitted to participate.
Institutional Review Board

The University of Newcastle and Charles Sturt University's Human Research Ethics Committee has approved this project. If you have any complaints or reservations about the ethical conduct of this project, you may contact the Committee through the Executive Officer. Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

<table>
<thead>
<tr>
<th>Executive Officer</th>
<th>Human Research Ethics Officer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Research Ethics Committee</td>
<td>Research Office</td>
</tr>
<tr>
<td>Office of Academic Governance</td>
<td>The Chancellery</td>
</tr>
<tr>
<td>Charles Sturt University</td>
<td>The University of Newcastle,</td>
</tr>
<tr>
<td>Panorama Avenue</td>
<td>University Drive</td>
</tr>
<tr>
<td>Bathurst NSW 2795</td>
<td>Cessnock NSW 2325, Australia</td>
</tr>
<tr>
<td>Phone: (02) 6338 4626</td>
<td>Telephone (02) 4921 6333</td>
</tr>
<tr>
<td>Fax: (02) 6338 4194</td>
<td>Email <a href="mailto:Human-Ethics@newcastle.edu.au">Human-Ethics@newcastle.edu.au</a></td>
</tr>
</tbody>
</table>

Informed Consent

If you agree to participate in this study, both you and your child need to please complete and sign the following informed Consent form.
Appendix 7.3

7.3 Consent Form

CONSENT FORM

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

Thank you for expressing interest in this research. If you agree to participate in this study, please complete and sign the following informed Consent form. Should you have any questions regarding this study the Chief Investigators may be contacted at any time.

Andrew Schaefer
(Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, 1st
Faculty of Science
Charles Sturt University
Panorama Ave, Bathurst, NSW 2795
Tel: 0457 344 259
Email: schaefer.86@myemail.csu.edu.au

Dr Susan Edwards
(Principal Supervisor)
School of Human Movement Studies
Allen House, 1st
Faculty of Science
Charles Sturt University
Panorama Ave, Bathurst, NSW 2795
Tel: 02) 6338 4522
Fax: 02) 6338 4455
Email: s.edwards@csu.edu.au

A/Prof Nicholas D'Heurle
(Principal Supervisor)
School of Human Movement Studies
Allen House, 1st
Faculty of Science
Charles Sturt University
Panorama Ave, Bathurst, NSW 2795
Tel: 02) 6338 4499
Fax: 02) 6338 4455
Email: n.dheurle@csu.edu.au

Dr Eduard Tardieu
(Principal Supervisor)
Discipline of Exercise and Sports Science
Faculty of Health Sciences
University of Sydney
75 East Road, Lidcombe NSW 1825
Tel: 02) 9351 9779
Fax: 02) 9351 6246
Email: eduard.tardieu@sydney.edu.au

________________________
[Print Name]

Consent Form: I, [Print Name], consent to participating in the research project titled "Investigation into the injury mechanisms associated with junior fast bowling across a season".

My consent to participate in this research is based on the following terms;

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.
2. I have read and understood the information sheet provided to me, and have retained a copy of the information sheet provided to me.
3. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked.
4. I am content that I understand what I will be required to do as research participant.
5. I understand that in the event of an injury all associated costs will lie with me, unless the injury was related solely to the negligence of Charles Sturt University.
6. I agree to undergo MRI of my lower back as part of the research project.
7. I agree to be photographed and videoed of my fast bowling technique throughout the duration of the research project.
8. I understand that any information or personal details gathered in the course of this research about me are confidential and that neither my name nor any other identifying information will be used or published without my written permission.
9. I understand that I can withdraw my consent at any time before, during, or after testing, without any penalty.

www.csu.edu.au
CRICOS Provider Numbers for Charles Sturt University are 00005F (NSW), 019470 (VC) and 02060B (ACT). ABN: 83 870 788 551
10. I nominate the person below as someone that can be contacted on my behalf in the unlikely event of an emergency:

Name: ______________________
Address: ____________________
Phone: ______________________

11. I am aware the Charles Sturt University's Human Research Ethics Committee has approved this study. I have approved this research. I understand that if I have any complaints or concerns about this research I can contact:

Executive Officer
Human Research Ethics Committee
Office of Academic Governance
Charles Sturt University
Panorama Avenue
Bathurst NSW 2796

Phone: (02) 6338 4628
Fax: (02) 6338 4194

Participant Print Name ____________________________
Signed ____________________________ Date ______/____/____
INFORMED & PARENTAL CONSENT FORM

INVESTIGATION INTO INJURY MECHANISMS
ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

Thank you for expressing interest in this research. If you and your child agree to participate in this study, please complete and sign the following informed Consent form, along with your child. It should be noted that you (Parent/Guardian) and your child must tick all the check boxes before you each sign this form. Should you or your child have any questions regarding this study the Chief Investigators may be contacted at any time.

Dr. Gazi Edwards
(Principal Investigator)
School of Environmental & Life Sciences
University of Newcastle
Clinksway Rd, Callaghan, NSW 2308
Tel: (02) 4362 4450
Email: gaziedwards@newcastle.edu.au

Andrew Schofer
(Associate Investigator)
School of Human Movement Studies
University of Newcastle
Clinksway Rd, Callaghan, NSW 2308
Tel: (02) 4362 4450
Email: a.schofer@newcastle.edu.au

AllProf Nicholas O’Driscoll
(Associate Investigator)
School of Human Movement Studies
University of Newcastle
Clinksway Rd, Callaghan, NSW 2308
Tel: (02) 4362 4450
Email: n.odriscoll@newcastle.edu.au

Dr. Edouard J. Andriantsiharana
(Associate Investigator)
Discipline of Exercise and Sports Science
University of Newcastle
Clinksway Rd, Callaghan, NSW 2308
Tel: (02) 4362 4450
Email: e.andriantsiharana@newcastle.edu.au

I, _____________________________ give my parental consent for _____________________________ to participating in the research project titled "Investigation into Injury mechanisms associated with Junior fast bowling across a season".

My consent for participation in this research is based on the following terms:

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.

2. I have read and understood the information sheet provided to me, and have retained a copy of the information sheet provided.

3. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked.

4. I am content that I understand what will be required of the research participant.

5. I understand that any information or personal details gathered in the course of this research about participants are confidential and that neither name nor any other identifying information will be used or published without written permission from both myself and my child.

6. I understand that in the event of an injury associated costs may be subsidised by the University, especially the injury was related to the negligence of The University of Newcastle or Charles Sturt University.

7. I have read and understood the MRI information sheet provided to me, and have retained a copy of the information sheet provided.
Appendix 7.3

<table>
<thead>
<tr>
<th>Child</th>
<th>Parent/Guardian</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

8. I agree to myself/my child undergoing an MRI of their lower back as part of the research project.

9. I agree to myself/my child undergoing a DXA scan of my/their body as part of the research project.

10. I understand that myself/my child will be videotaped and/or photographed as a part of this research.

11. I understand that myself/my child can withdraw consent at any time before, during, or after testing, without any penalty.

12. I nominate the person below as someone that can be contacted on my behalf in the unlikely event of an emergency:

   Name: ______________________________
   Address: __________________________
   Phone: ____________________________

13. I am aware the University of Newcastle and Charles Sturt University’s Human Research Ethics Committee has approved this study. I have approved this research. I understand that if I have any complaints or concerns about this research I can contact:

   Executive Officer
   Human Research Ethics Committee
   Office of Academic Governance
   Charles Sturt University
   Panorama Avenue
   Bathurst NSW 2795
   T +61 2 6338 4628
   F +61 2 6338 4194

   Research Services
   Research Integrity Unit
   The Chancellery
   The University of Newcastle
   Callaghan NSW 2308
   T +61 2 492 17884
   F +61 2 492 17164
   Human-Ethics@newcastle.edu.au

Participant Print Name

Signed

Date

Parent/Guardian Print Name

Signed

Date
7.4 Parental Consent Form

PARENTAL CONSENT FORM

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

Your child has expressed an interest in being a participant in this research. If you agree for your child to participate in this study, please complete and sign the following Parental Informed Consent form. Should you have any questions regarding this study the Chief Investigators may be contacted at any time.

Andrew Schoeler
(Principal Investigator)
PhD Student
School of Human Movement Studies
Charles Sturt University
Pannawonica Ave, Bathurst, NSW 2795
Mob: 0487 244 258
Email: schooler.as@csu.edu.au

Dr Suad Elmore
(Principal Supervisor)
School of Human Movement Studies
Charles Sturt University
Pannawonica Ave, Bathurst, NSW 2795
Tel: (02) 6338 4506
Fax: (02) 6338 4665
Email: mulpiner@csu.edu.au

Alk Prof Nicholas O’Deary
(Associate Supervisor)
School of Human Movement Studies
Charles Sturt University
Pannawonica Ave, Bathurst, NSW 2795
Tel: (02) 6338 4506
Fax: (02) 6338 4665
Email: nicholas.odeary@csu.edu.au

Dr Eduard Ferdinand
(Associate Supervisor)
Faculty of Health Sciences
University of Sydney
75 East Rd, Lutonber NSW 1625
Tel: (02) 9351 8778
Fax: (02) 9351 9264
Email: eferdinand@uni.sydney.edu.au

I, ____________________________________________________________ (Parent’s name) give my parental consent for _________________________________________________________ (Parent’s child’s name) to participating in the research project titled “Investigation into injury mechanisms associated with junior fast bowling across a season.”

My consent for participation in this research is based on the following terms:

1. The purpose of the research has been explained to me and my child, including the potential risks and discomforts involved.  □
2. I have read and understood the information sheet provided to me and my child, and have retained a copy of the information sheet provided. □
3. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked. □
4. I am content that I understand what will be required of the research participant. □
5. I understand that any information or personal details gathered in the course of this research about participants are confidential and that neither name nor any other identifying information will be used or published without written permission from both myself and my child. □
6. I agree to my child undergoing an MRI of their lower back as part of the research project □
7. I understand that participants will be videotaped and/or photographed as a part of this research. □
8. I understand that participants can withdraw consent at any time before, during, or after testing, without any penalty. □
9. I nominate the person below as someone that can be contacted on my behalf in the unlikely event of an emergency:

Name: 
Address: 
Phone: 

10. I am aware the Charles Sturt University's Human Research Ethics Committee has approved this study has approved this research. I understand that if I have any complaints or concerns about this research I can contact:

Executive Officer
Human Research Ethics Committee
Office of Academic Governance
Charles Sturt University
Panorama Avenue
Bathurst NSW 2786

Phone: (02) 6338 4628
Fax: (02) 6338 4194

Parent/Guardian Post Name: ____________________________
Signed: ____________________________
Date: ____________________________
Physical Activity Readiness Questionnaire (PAR-Q)

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential.

If you are between the ages of 15 and 69 years, the PAR-Q will tell you if you should check with your doctor before you consent and participate in being a subject in the study "Investigation into injury mechanisms associated with junior fast bowling across a season". Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES NO

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
2. Do you feel pain in your chest when you do physical activity?
3. In the past month, have you had chest pain when you were not doing physical activity?
4. Do you lose your balance because of dizziness or do you ever lose consciousness?
5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?
6. Is your doctor currently prescribing drugs (for example, water pills) for blood pressure or a heart condition?
7. Do you know of any other reason why you should not do physical activity?

Yes to two or more questions

Talk with your doctor in person. Tell your doctor about the PAR-Q and which questions you answered YES. Talk with your doctor about the study "Investigation into injury mechanisms associated with junior fast bowling across a season" that you wish to participate in and have a medical screening by your doctor. Follow your doctor’s advice. If you are able to consent to this study, you will require a letter of consent from your doctor approving your participation in the study.

No to all questions

If you answered NO honestly to all PAR-Q questions, you can become a subject in the study "Investigation into injury mechanisms associated with junior fast bowling across a season".

DELAY BECOMING A SUBJECT IN THE STUDY

If you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better before you consent and participate as a subject in the study.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell the Chief Investigator of the study, Andrew Schaefer (PhD student, School of Human Movement, Charles Sturt University, Bathurst (0457 244 259)).

www.csu.edu.au
CRICOS Provider Numbers for Charles Sturt University are 00005F (NSW), 01947G (NC) and 02960B (ACT). ABN: 83 678 708 551
Physical Activity Readiness Questionnaire (PAR-Q)

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential.

If you are between the ages of 15 and 69 years, the PAR-Q will tell you if you should check with your doctor before you consent and participate to being a subject in the study “Investigation into injury mechanisms associated with junior fast bowling across a season”. Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES NO

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

2. Do you feel pain in your chest when you do physical activity?

3. In the past month, have you had chest pain when you were not doing physical activity?

4. Do you lose your balance because of dizziness or do you ever lose consciousness?

5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?

6. Is your doctor currently prescribing drugs (for example, water pills) for blood pressure or a heart condition?

7. Do you know of any other reason why you should not do physical activity?

Yes to two or more questions

Talk with your doctor in person. Tell your doctor about the PAR-Q and which questions you answered YES. Talk with your doctor about the study "Investigation into injury mechanisms associated with junior fast bowling across a season", that you wish to participate in and have a medical screening by your doctor. Follow your doctor’s advice. If you are able to consent to this study, you will require a letter of consent from your doctor approving your participation in the study.

No to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can become a subject in the study “Investigation into injury mechanisms associated with junior fast bowling across a season”.

DELAY BECOMING A SUBJECT IN THE STUDY

If you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better before you consent and participate as a subject in the study.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell the Chief Investigator of the study, Andrew Schaefer (PhD student, School of Human Movement, Charles Sturt University, Bathurst (Ph: 0457 244 259).
Appendix 7.6

7.6 Coronary Artery Disease Risk Factor Stratification

Coronary Artery Disease Risk Factor Stratification

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential;

Coronary Artery Disease Risk Factor Stratification will tell you if you should check with your doctor before you consent and participate in the study “INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON”. Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES NO

- Family history of heart attack, or sudden death before 55 years of age in father or other male first-degree relative (i.e., brother or son), or before 65 years of age in mother or other first-degree female relative (i.e., sister or daughter)
- Current cigarette smoker or have quit within the last 6 months
- High blood pressure or on high blood pressure medication
- High cholesterol levels
- Impaired fasting glucose
- Obesity
- Sedentary lifestyle

Yes to two or more questions

Talk with your doctor in person. Tell your doctor about the Coronary Artery Disease Risk Factor Stratification and which questions you answered YES. Talk with your doctor about the study, “INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON”, that you wish to participate in, and have a medical screening by your doctor. Follow your doctor’s advice. If you are able to consent to this study, you will require a letter of consent from your doctor approving your participation in the study.

Yes to less than two questions

If you answered yes to less than two questions honestly in the Coronary Artery Disease Risk Factor Stratification, you can be reasonably sure that you can become a subject in the study “INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON”.

www.csu.edu.au

ORCOS Provider Numbers for Charles Sturt University are 00045F (NSW), 01947G (VIC) and 02660B (ACT). ABN: 83 878 708 581

182
Coronary Artery Disease Risk Factor Stratification

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential.

Coronary Artery Disease Risk Factor Stratification will tell you if you should check with your doctor before you consent and participate to be a participant in the study “Investigation into injury mechanisms associated with junior fast bowling across a season”. Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES  NO

- Family history of heart attack, or sudden death before 55 years of age in father or other male first-degree relative (i.e., brother or son), or before 65 years of age in mother or other first-degree female relative (i.e., sister or daughter)
- Current cigarette smoker or have quit within the last 6 months
- High blood pressure or on high blood pressure medication
- High cholesterol levels
- Impaired fasting glucose
- Obesity
- Sedentary lifestyle

Yes to two or more questions

Talk with your doctor in person. Tell your doctor about the Coronary Artery Disease Risk Factor Stratification and which questions you answered YES. Talk with your doctor about the study, “Investigation into injury mechanisms associated with junior fast bowling across a season”, that you wish to participate in, and have a medical screening by your doctor. Follow your doctor’s advice. If you are able to consent to this study, you will require a letter of consent from your doctor approving your participation in the study.

Yes to less than two questions

If you answered yes to less than two questions honestly in the Coronary Artery Disease Risk Factor Stratification, you can be reasonably sure that you can become a subject in the study “Investigation into injury mechanisms associated with junior fast bowling across a season”.
7.7 Injury History Questionnaire

INJURY HISTORY QUESTIONNAIRE

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential;

Surname: _______________ First name: _______________ DOB: ___ / ___ / ___ Age: __________

Address: __________________________

Phone (H): _______________ (Mob): _______________ Email: _______________

Occupation: __________________________ Hgt: __________ cm Wgt: __________ kg

Injuries: __________________________

DETAILS OF LEVEL OF COMPETITION/TRAINING

1. In what age group(s) do you play cricket?
   - [ ] Under 13s  [ ] Under 14s  [ ] Under 15s  [ ] Under 16s  [ ] Under 17s
   - [ ] Under 18s  [ ] Under 19s  [ ] Senior

2. Do you participate in any other sports (tick answer)? [ ] Yes  [ ] No
   If yes please specify: __________________________

3. What level(s) of cricket do you compete in?
   - [ ] Local  [ ] District  [ ] Zone  [ ] State  [ ] National

4. How many overs do you complete in a game (on average)?
   - [ ] 0-1  [ ] 2-3  [ ] 4-5  [ ] 6-7  [ ] >7

5. How many hours per week do you train for cricket?
   - [ ] 0-1  [ ] 2-3  [ ] 4-5  [ ] >5

6. How many overs in a spell do you complete in a game (on average)?
   - [ ] 0-1  [ ] 2-3  [ ] 4-5  [ ] >5

7. Do you do any other type of training specifically for your sport other than your cricket training (e.g. weights, plyometrics, running etc.)?
   [ ] Yes  [ ] No

If so, list the types of training and hours of training

www.csu.edu.au
CIRCO55 Provider Numbers for Charles Sturt University are 00055 (NSW), 019475 (VC) and 02960B (ACT). ABN: 83 879 708 551
1. List any other physical activity(s) that you are currently involved in on a regular basis (more than once per week)?

**HISTORY OF INJURIES**

2. Have you ever sustained any major **lower limb injury(s)** (ankle, knee or hip) that required medical attention or disturbed your normal activities for more than one week?  
   [ ] Yes  [ ] No  
   (If yes, please specify what injuries in the table below)

<table>
<thead>
<tr>
<th>Lower Limb Injury(s)</th>
<th>&lt; 12 months</th>
<th>1-5 years</th>
<th>&gt; 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 7.7

3. Have you ever sustained any major **upper limb injury(s)** (shoulder, elbow or wrist) that required medical attention or disturbed your normal activities for more than one week? (If yes, what injuries)

   - Yes
   - No (if yes, please specify what injuries in the table below)

<table>
<thead>
<tr>
<th>Upper Limb Injuries</th>
<th>&lt; 12 months</th>
<th>1-5 years</th>
<th>&gt; 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Type of Injury</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sport or Activity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occurred</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of Sport</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Do you have any current injury or illness which may impede your participation in the task described in the Participant Information Package?

   - Yes
   - No

If so, please describe.
5. Have you ever sustained any **back injuries** that required medical attention or disturbed your normal activities for more than one week?
   - Yes  
   - No (if no, you have no completed this questionnaire)

**A. INFORMATION ON PREVIOUS LOWER BACK INJURIES**

6. What type(s) of back injury did you sustain?
   - L4/L5 stress fracture  
   - Bulging intervertebral disc  
   - Spondyloysis  
   - Spondyloisthesis  
   - Pars interarticularis  
   - Other
   
   If other please specify:__________________________

7. How many previous lower back injury/trimes of pain have you sustained?
   - 0  
   - 1  
   - 2  
   - 3  
   - 4  
   - 5  
   - >5

8. How long did you sustain your last back injury?
   - 0-3 months  
   - 6 months  
   - 12 months  
   - >12 months  
   - 1-2 years  
   - >2 years

9. What was the severity of your last back injury?
   - Minor  
   - Moderate  
   - Serious  
   - Severe

10. For how long were you unable to fully play/train for your last back injury?
    - 1-3 days  
    - 4-7 days  
    - 1-4 weeks  
    - >4 weeks

11. During what activity(s) did you sustain your last back injury(s)?
    - Fast bowling  
    - Other, please specify: ________________________________

12. What type of treatment did you receive for the last injury?
    - Surgery  
    - Physiotherapy  
    - None  
    - Don't know
<table>
<thead>
<tr>
<th>Topic of Week</th>
<th>Sub-topic</th>
<th>Learning Objectives</th>
<th>Assessment</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7.7: Sample Table and Diagram*
INJURY HISTORY QUESTIONNAIRE

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential;

Surname: ___________________________ First name: ___________________________ DOB: ___ / ___ / ___ Age: ______

Address: ____________________________________________

Phone (H): __________________________ (Mob): __________________________ Email: __________________________

Occupation: ___________________________ Hgt: ______ cm Wgt: ______ kg

GENERAL PRACTITIONER INFORMATION

If any serious medical issues should be revealed due to MRI as indicated by the radiologists’ report, then this report will be relayed immediately to the participant and guardian, and their GP to discuss the unexpected medical issue. Therefore, to ensure no delay in passing on the relevant medical information to your GP, your details of your GP is required.

a. Doctors Name: ___________________________

b. Phone Number: ___________________________

c. Email address: ___________________________

DETAILS OF LEVEL OF COMPETITION/TRAINING

1. In what age group(s) do you play cricket?
   - [ ] Under 13s  [ ] Under 14s  [ ] Under 15s  [ ] Under 16s  [ ] Under 17s
   - [ ] Under 18s  [ ] Under 19s  [ ] Senior

2. Do you participate in any other sports (tick answer)? [ ] Yes  [ ] No
   If yes please specify: ___________________________

3. What level(s) of cricket do you compete in?
   - [ ] Local  [ ] District  [ ] Zone  [ ] State  [ ] National

4. How many overs do you complete in a game (on average)?
   - [ ] 2-3  [ ] 4-5  [ ] 6-7  [ ] >7

5. How many hours per week do you train for cricket?
   - [ ] 0-1  [ ] 2-3  [ ] 4-5  [ ] >5
6. How many overs in a spell do you complete in a game (on average)?
   - 0-1
   - 2-3
   - 4-5
   - >5

7. Do you do any other type of training specifically for your sport other than your cricket training (e.g. weights, plyometrics, running etc)?
   - Yes
   - No

   If so, lists the types of training and hours of training

2. List any other physical activity(s) that you are currently involved in on a regular basis (more than once per week)?
3. Have you ever sustained any major **lower limb injury(s)** (ankle, knee or hip) that required medical attention or disturbed your normal activities for more than one week?

- **Yes**
- **No**

(If yes, please specify what injuries in the table below)

<table>
<thead>
<tr>
<th>Lower Limb Injury(s)</th>
<th>&lt; 12 months</th>
<th>1-5 years</th>
<th>&gt; 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
</tbody>
</table>

|                      | Right       | Left      | Right     | Left      |

|                      | Right       | Left      | Right     | Left      |

- **Type of Injury**

- **Severity**

- **Sport or Activity Occurred**

- **Level of Sport**
4. Have you ever sustained any major upper limb injury(s) (shoulder, elbow or wrist) that required medical attention or disturbed your normal activities for more than one week? (If yes, what injuries)
   - Yes
   - No (if yes, please specify what injuries in the table below)

<table>
<thead>
<tr>
<th>Upper Limb Injuries</th>
<th>&lt; 12 months</th>
<th>1-4 years</th>
<th>&gt; 4 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Type of Injury</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sport or Activity Occurred</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of Sport</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Do you have any current injury or illness which may impede your participation in the task described in the Participant Information Package?
   - Yes
   - No

If so, please describe.
6. Have you ever sustained any **back injuries** that required medical attention or disturbed your normal activities for more than one week?

☐ Yes  ☐ No (if no, you have no completed this questionnaire)

A. **INFORMATION ON PREVIOUS LOWER BACK INJURIES**

7. What type(s) of back injury did you sustain?

☐ L4/L5 stress fracture  ☐ Bulging intervertebral disc  ☐ Spondylothesis  ☐ Spondylolysis  ☐ Other

If other please specify: ____________________________________________

8. How many previous lower back injury/times of pain have you sustained?

☐ 0  ☐ 1  ☐ 2  ☐ 3  ☐ 4  ☐ 5  ☐ >5

9. How long did you sustain your last back injury?

☐ 0-3 months  ☐ 6 months  ☐ 12 months  ☐ >12 months  ☐ 1-2 years  ☐ >2 years

10. What was the severity of your last back injury?

☐ Minor  ☐ Moderate  ☐ Serious  ☐ Severe

11. For how long were you unable to fully play/train for your last back injury?

☐ 1-3 days  ☐ 4-7 days  ☐ 1-4 weeks  ☐ >4 weeks

12. During what activity(s) did you sustain your last back injury(s)?

☐ Fast bowling  ☐ Other, please specify: ____________________________________________

13. What type of treatment did you received for the last injury:

☐ surgery  ☐ physiotherapy  ☐ none  ☐ don’t know
7.8 Manuscript 1 - Methods

7.8.1 Cohort Differences in Pitch Surface

The distribution of action types was slightly higher for mixed and lower for semi-open in cohort 3 (Table 7-1). The GRFs between the two pitch surface types found a significant interaction of force*pitch ($F_{6,342}=23.02$, $P<0.05$; Figure 7-1), with posterior ground reaction force significantly greater in the no running track group.

Table 7-1 Distribution of action types for the running track and no running track groups. Percentage breakdown of total action types per group.

<table>
<thead>
<tr>
<th>Action type</th>
<th>Running track (n=37)</th>
<th>No running track (n=23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-on</td>
<td>1 (3%)</td>
<td>1 (4%)</td>
</tr>
<tr>
<td>Front-on</td>
<td>9 (24%)</td>
<td>5 (22%)</td>
</tr>
<tr>
<td>Semi-open</td>
<td>14 (38%)</td>
<td>12 (52%)</td>
</tr>
<tr>
<td>Mixed</td>
<td>13 (35%)</td>
<td>5 (22%)</td>
</tr>
</tbody>
</table>

![Graph showing mean (± SE) values of peak ground reaction forces between cohort 1-2 and cohort 3.](image)

Figure 7-1 Mean (± SE) values of peak ground reaction forces between cohort 1-2 and cohort 3.
7.9 **Manuscript 2 - Results**

### 7.9.1 Rear-leg and Bowling Arm Angles

Back-foot lower limb joint angles at BIC and FIC found no significant main effect of LSA ($F_{1,18}=1.28$, $P=0.27$, $\eta^2_p = 0.0662$) nor any interaction for angles*stages*LSA ($F_{8,144}=1.44$, $P=0.19$, $\eta^2_p = 0.074$; Figure 7-4A). For bowling arm joint angles, the results showed a significant main effect of LSA ($F_{1,18}=10.78$, $P=0.004$, $\eta^2_p = 0.3746$) and also a significant interaction for angles*stages*injury ($F_{30,540}=1.51$, $P=0.04$, $\eta^2_p = 0.0773$; Figure 7-4B). **Post-hoc** analyses found a significant increase at BIC of shoulder internal rotation and elbow pronation for LSA compared to non-injured.

### 7.9.2 Lower Limb Joint Moments

For lower limb joint moments, no significant main effect was observed for LSA ($F_{1,18}=0.11$, $P=0.08$, $\eta^2_p = 0.0063$). There was a significant interaction for moments*LSA ($F_{17,306}=1.8$, $P=0.03$, $\eta^2_p = 0.0906$; Figure 7-3), but **post-hoc** analyses showed no significant results.
Figure 7-2  Mean (± SE) values of 9 lower limb joint angles at back-foot contact phase (A) and 7 bowling arm joint angles (B) across stages of the bowling action and non-injured/LSA groups. The following rotations are positive: ankle dorsiflexion, inversion, forefoot adduction, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction, hip internal rotation, shoulder forward flexion, shoulder adduction, shoulder internal rotation, elbow flexion, elbow pronation, wrist flexion and ulnar deviation. N.B. * denotes significant results.
Figure 7-3  Mean (± SE) values of peak lower limb joint moments (relative mass x height) for non-injured and LSA groups.
7.10 Manuscript 4 - Results

7.10.1 Rear-leg and Bowling Arm Angles

For back leg joint angles, no significant main effect of group (F_{1,19}=0.1, P=0.76, \eta_p^2 = 0.0052) but there was intervention (F_{1,19}=5.14, P=0.04, \eta_p^2 = 0.213). Also there was no observed significant interaction for group*intervention*stage*angle (F_{8,152}=1.02, P=0.42, \eta_p^2 = 0.051; Figure 7-4).

No significant main effect of group was found for bowling arm angles (F_{1,19}=0.0005, P=0.98, \eta_p^2 = 0.0000) or intervention (F_{1,19}=0.36, P=0.56, \eta_p^2 = 0.0184), while a significant interaction was found for group*intervention*stage*angle (F_{30,570}=3.39, P>0.05, \eta_p^2 = 0.1515) with the post-hoc analysis results presented in Table 7-2.

7.10.2 Lower Limb Joint Moments

For lower limb joint moments, no significant main effect was observed for LSA for group (F_{1,19}=1.17, P=0.29, \eta_p^2 = 0.0579) but a significant effect of intervention was observed (F_{1,19}=66.1, P<0.05, \eta_p^2 = 0.7767) with a greater mean moment at post-intervention (2.73±0.11 relative BM x height) than pre-intervention (1.81±0.08 relative BM x height). Also no significant interaction was observed for moments*LSA (F_{17,306}=1.18, P=0.28, \eta_p^2 = 0.0485 Figure 7-10).
Table 7-2  Mean (± SE) of significant interactions for bowling arm joint angles between control and coaching groups.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Phase</th>
<th>P value</th>
<th>M±SE°</th>
<th>M±SE°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (Pre) v Coach (Pre)</td>
<td>Elb pro</td>
<td>BIC</td>
<td>&gt;0.05</td>
<td>65.3±20.8</td>
</tr>
<tr>
<td>Control (Post) v Coach (Post)</td>
<td>Sh IR</td>
<td>BIC</td>
<td>&gt;0.05</td>
<td>22.2±15.9</td>
</tr>
<tr>
<td>Coach (Pre) v Post</td>
<td>Elb pro</td>
<td>BIC</td>
<td>&gt;0.05</td>
<td>72.1±25.6</td>
</tr>
<tr>
<td></td>
<td>Sh IR</td>
<td>BIC</td>
<td>&gt;0.05</td>
<td>13.9±12.5</td>
</tr>
<tr>
<td>Coach (Pre v Post)</td>
<td>Elb Flex</td>
<td>BIC</td>
<td>&gt;0.05</td>
<td>35.9±7.5</td>
</tr>
<tr>
<td></td>
<td>Elb IR</td>
<td>BIC</td>
<td>&gt;0.05</td>
<td>98.2±19.9</td>
</tr>
<tr>
<td></td>
<td>Elb IR</td>
<td>AH</td>
<td>0.02</td>
<td>73.6±7.1</td>
</tr>
</tbody>
</table>
Figure 7-4  Mean (± SE) values of 9 lower limb joint angles at back-foot contact across stages of the bowling action and control and coaching groups. The following rotations are positive: ankle dorsiflexion, inversion, forefoot adduction, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction and hip internal rotation.
Figure 7-5  Mean (± SE) values of 9 lower limb joint angles at front-foot contact across stages of the bowling action and control and coaching groups. The following rotations are positive: ankle dorsiflexion, inversion, forefoot adduction, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction and hip internal rotation.
Figure 7-6  Mean (± SE) values of 6 torso joint angles at AV between control and coaching groups. The following rotations are positive: L5S1 flexion, L5S1 left lateral flexion, L5S1 right rotation, T12L1 flexion, T12L1 left lateral flexion and T12L1 right rotation.
Figure 7-7  Mean (± SE) values of trunk-pelvis angle across stages of the bowling action between control and coaching groups. The following rotations are positive: trunk-pelvis extension, trunk-pelvis right flexion and trunk-pelvis left rotation.
Figure 7-8  Mean (± SE) values of peak torso joint velocity over 4 phases of the bowling action between control and coaching groups.
Figure 7-9  Mean (± SE) values of crunch factors over 5 phases of the bowling action between control and coaching groups.
Figure 7-10  Mean (± SE) values of peak lower limb joint moments (relative mass x height) between control and coaching groups.
### 7.10.3 Coaching Intervention Attendance

<table>
<thead>
<tr>
<th>Bowler</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
<th>Session 5</th>
<th>Session 6</th>
<th>Session 7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>57</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>87</td>
</tr>
<tr>
<td>6</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>71</td>
</tr>
<tr>
<td>8</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>71</td>
</tr>
<tr>
<td>9</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>57</td>
</tr>
<tr>
<td>10</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>71</td>
</tr>
<tr>
<td>11</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>57</td>
</tr>
</tbody>
</table>
### 7.11 Glossary of Key Terms and Abbreviations

#### 7.11.1 Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-Foot Contact Phase</td>
<td>The period of time during the fast bowling action beginning at back-foot initial contact (BIC) and ending at front-foot initial contact (FIC).</td>
</tr>
<tr>
<td>Batsmen</td>
<td>A cricket player whose primary skill is in batting.</td>
</tr>
<tr>
<td>Bowling</td>
<td>The action of projecting a cricket ball towards a batsman’s wicket/stumps.</td>
</tr>
<tr>
<td>Cardan Sequence</td>
<td>A sequence used to define the sequence of a joint angle (e.g. XYZ).</td>
</tr>
<tr>
<td>Cartesian Local Coordinate System</td>
<td>A coordinate system specifying a point on a plane by a pair of numerical coordinates. These are the positive/negative distances to the point from two fixed perpendicular directed lines.</td>
</tr>
<tr>
<td>Contralateral</td>
<td>Denotes the side of the body opposite to that on which a particular structure or condition occurs.</td>
</tr>
<tr>
<td>Crunch Factor</td>
<td>The instantaneous product of the velocity or displacement of two or more planes of one or more adjacent body segments.</td>
</tr>
<tr>
<td>Delivery</td>
<td>The action of bowling a cricket ball.</td>
</tr>
<tr>
<td>Front-Foot Contact Phase</td>
<td>The period of time during the fast bowling action beginning at front-foot initial contact (FIC) and ending at bowling upper-arm vertical (AV).</td>
</tr>
<tr>
<td>Front-On Action</td>
<td>Bowling action where the back foot lands in line with the pitch, while shoulder alignment (&gt;50°) is facing the batsman and counter-rotation is &lt;30°.</td>
</tr>
<tr>
<td><strong>Impulse</strong></td>
<td>The time over which a force acts (Force multiplied by the difference in time).</td>
</tr>
<tr>
<td><strong>Incidence</strong></td>
<td>A measure of the probability that a given condition will occur in a population within a specified period of time or the number of new cases during some time period.</td>
</tr>
<tr>
<td><strong>Ipsilateral</strong></td>
<td>Belonging to or occurring on the same side of the body.</td>
</tr>
<tr>
<td><strong>Joint Moment</strong></td>
<td>The product of a linear force and the distance from the muscle's line of action to the joint's centre of rotation (moment arm).</td>
</tr>
<tr>
<td><strong>Kinematic</strong></td>
<td>The motion of objects without reference to the forces which cause the motion.</td>
</tr>
<tr>
<td><strong>Kinetic</strong></td>
<td>The motion of objects with reference to the forces which cause the motion.</td>
</tr>
<tr>
<td><strong>Loading rate</strong></td>
<td>The speed in which a force or forces are applied to the human body.</td>
</tr>
<tr>
<td><strong>Lumbar Spine Abnormality</strong></td>
<td>Any variation from the typical lumbar spine anatomy.</td>
</tr>
<tr>
<td><strong>Mixed Action</strong></td>
<td>Bowling action where the bowler begins with the chest facing towards the batsman at initial back foot-ground contact and then rotates the shoulder to a side-on alignment before ground impact of the front foot.</td>
</tr>
<tr>
<td><strong>Movement Variability</strong></td>
<td>The normal variations that occur during multiple repetitions of a task.</td>
</tr>
<tr>
<td><strong>Oedema</strong></td>
<td>An excess of watery fluid collecting in the cavities or tissues of the body.</td>
</tr>
<tr>
<td><strong>Over</strong></td>
<td>Six consecutive balls bowled by a single bowler from one end of a cricket pitch.</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Pars Interarticularis</td>
<td>A small segment of bone that joins the facet joints in the back of the spine.</td>
</tr>
<tr>
<td>Pedicle Sclerosis</td>
<td>Abnormal hardening of the segment between the transverse process and the vertebral body.</td>
</tr>
<tr>
<td>Pitch</td>
<td>A flat, extremely short grass covered central strip of the cricket field between the wickets measuring 20.12m long and 3.05m wide.</td>
</tr>
<tr>
<td>Semi-Open Action</td>
<td>Where the bowler has a back-foot shoulder alignment between 25° and 50° and shoulder counter-rotation &lt;30°.</td>
</tr>
<tr>
<td>Shoulder Counter-Rotation</td>
<td>The amount of rotation of the shoulders from back-foot initial contact (BIC) to the most side on point of the bowling action.</td>
</tr>
<tr>
<td>Shoulder-Pelvis Separation Angle</td>
<td>The difference between the rotation of the hip and shoulder segments.</td>
</tr>
<tr>
<td>Side-On Action</td>
<td>Where the bowler lands with the back foot contacting the ground parallel to the wicket and the body positioned so that the leading shoulder is directed down the line of the pitch.</td>
</tr>
<tr>
<td>Spondylolisthesis</td>
<td>A condition where one vertebral body slips forward over another.</td>
</tr>
<tr>
<td>Spondylolysis</td>
<td>A condition in which the there is a defect to the pars interarticularis.</td>
</tr>
<tr>
<td>Stress Fracture</td>
<td>A fracture of a bone caused by repeated mechanical stress.</td>
</tr>
<tr>
<td>Temporal</td>
<td>Relating to time.</td>
</tr>
</tbody>
</table>
7.11.2 *Abbreviations*

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>AH</td>
<td>Upper bowling-arm horizontal</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AV</td>
<td>Upper bowling-arm vertical</td>
</tr>
<tr>
<td>BIC</td>
<td>Back-foot initial contact</td>
</tr>
<tr>
<td>BM</td>
<td>Body mass</td>
</tr>
<tr>
<td>BR</td>
<td>Ball-release</td>
</tr>
<tr>
<td>BW</td>
<td>Body weight</td>
</tr>
<tr>
<td>CF</td>
<td>Crunch factor</td>
</tr>
<tr>
<td>FIC</td>
<td>Front-foot initial contact</td>
</tr>
<tr>
<td>Flex-ext</td>
<td>Flexion-extension</td>
</tr>
<tr>
<td>FV</td>
<td>Peak vertical ground reaction force</td>
</tr>
<tr>
<td>GRF</td>
<td>Ground reaction force</td>
</tr>
<tr>
<td>L5-S1</td>
<td>Lumbar vertebrae 5 - sacral vertebrae 1 space</td>
</tr>
<tr>
<td>Lat flex</td>
<td>Lateral flexion</td>
</tr>
<tr>
<td>LSA</td>
<td>Lumbar spine abnormality</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of motion</td>
</tr>
<tr>
<td>Rot</td>
<td>Rotation</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>T12-L1</td>
<td>Thoracic vertebrae 12 - lumbar vertebrae 1 space</td>
</tr>
</tbody>
</table>