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A BIOMECHANICAL ANALYSIS OF
FAST BOWLING IN CRICKET

by

Peter John Worthington

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy at Loughborough University

June 2010

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ABSTRACT

A biomechanical analysis of fast bowling in cricket

Peter John Worthington, Loughborough University, 2010

Full-body three-dimensional kinematics and ground reaction force characteristics were calculated to enable the analysis of fast bowling techniques. In particular, the effect of interactions between aspects of fast bowling technique on ball release speed and ground reaction forces. A three-dimensional full-body inverse dynamics analysis was developed allowing forces in the lower back to be estimated and their link with bowling technique addressed. The bowler was represented by a system of 18 rigid segments connected by pin joints. Kinematic (300 Hz) and kinetic (1008 Hz) data were collected for a group of 20 elite fast bowlers, using an 18 camera Vicon Motion Analysis System and a Kistler force plate. Each bowler performed six maximal velocity deliveries, striking the force plate with their front foot during the front foot contact phase of the bowling action. The best three deliveries – maximal velocity deliveries with minimal marker loss – were analysed for each bowler. The analysis was customised for each bowler using subject specific segmental properties. Parameters were calculated describing elements of fast bowling technique as well as characteristics of the ground reaction forces. The effect of these technique parameters on: ball release speed; peak ground reaction forces; and peak forces in the lower back were addressed using linear regression. The results suggest the fastest bowlers had a quicker run-up and maintained a straighter front knee throughout the front foot contact phase of the bowling action. The fastest bowlers also exhibited larger amounts of thoracic flexion, between front foot contact and ball release, and appeared to delay the onset of upper arm circumduction. These four aspects of technique explained 74% of the variation observed in ball release speed. Faster ball release speeds were associated with a larger braking impulse between front foot contact and ball release, in addition to lower peak loading rates. The results also indicate that the peak ground reaction forces and the peak forces in the lower back are determined predominantly by the initial orientation of the front leg at the instant of front foot contact.
PUBLICATIONS

Published Papers:


Conference Presentations:


Significant contributions were also made to:

ACKNOWLEDGEMENTS

I would like to thank Loughborough University and the England and Wales Cricket Board for the opportunity to do this study – in particular my supervisors Dr Mark King and Dr Craig Ranson as well as Troy Cooley who was the initial driving force behind this study. Thanks should also go to Kevin Shine, whose enthusiasm for this study was invaluable.

I would also like to thank all of the members of the sports biomechanics research group, who provided crucial manpower for the data collection sessions and provided knowledge without which this study would not have been possible.

Finally, I would like to thank my family and friends for their support and encouragement. Special thanks should be made to my parents whose statistical expertise was key to the progress of this study.
DEDICATION

To my family and friends
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUBLICATIONS</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
</tbody>
</table>

## CHAPTER 1: INTRODUCTION

1.1 THE AREA OF STUDY                           | 1  |
1.2 STATEMENT OF PURPOSE                       | 3  |
1.3 RESEARCH QUESTIONS                         | 4  |
1.4 CHAPTER ORGANISATION                       | 5  |

## CHAPTER 2: REVIEW OF THE LITERATURE

2.1 ACTION CLASSIFICATION AND TERMINOLOGY      | 7  |
2.2 LOWER BACK INJURIES IN FAST BOWLING        | 11 |
2.2.1 SHOULDER COUNTER-ROTATION                | 14 |
2.2.2 PELVIS-SHOULDER SEPARATION ANGLE         | 15 |
2.2.3 FRONT LEG KINEMATICS                     | 17 |
2.2.4 OTHER FACTORS                            | 19 |
2.2.5 THREE-DIMENSIONAL KINEMATICS DURING THE FRONT FOOT CONTACT PHASE | 20 |
2.3 KINETICS OF FAST BOWLING                   | 22 |
2.4 FAST BOWLING TECHNIQUE AND BALL RELEASE SPEED | 27 |
2.4.1 RUN-UP SPEED                              | 27 |
2.4.2 DELIVERY STRIDE                          | 29 |
2.4.3 FRONT KNEE TECHNIQUE                     | 29 |
2.4.4 THORACIC MOTION                          | 31 |
2.4.5 BOWLING ARM                              | 32 |
2.5 CHAPTER SUMMARY                            | 33 |

## CHAPTER 3: DATA COLLECTION AND PROCESSING

3.1 EQUIPMENT                                  | 34 |
3.2 PARTICIPANTS                               | 36 |
3.3 MARKERS                                    | 37 |
3.4 TESTING PROTOCOL                           | 38 |
### CHAPTER 4: DATA ANALYSIS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>18 SEGMENT REPRESENTATION OF A BOWLER</td>
<td>45</td>
</tr>
<tr>
<td>4.2</td>
<td>SEGMENTATION OF THE BACK</td>
<td>46</td>
</tr>
<tr>
<td>4.3</td>
<td>JOINT CENTRE LOCATIONS</td>
<td>47</td>
</tr>
<tr>
<td>4.3.1</td>
<td>HIP JOINT CENTRES</td>
<td>47</td>
</tr>
<tr>
<td>4.3.2</td>
<td>JOINT CENTRES OF THE BACK</td>
<td>48</td>
</tr>
<tr>
<td>4.4</td>
<td>SEGMENT DEFINITIONS</td>
<td>49</td>
</tr>
<tr>
<td>4.4.1</td>
<td>PELVIS SEGMENT</td>
<td>50</td>
</tr>
<tr>
<td>4.4.2</td>
<td>UPPER AND LOWER-BACK SEGMENTS</td>
<td>50</td>
</tr>
<tr>
<td>4.4.3</td>
<td>HEAD AND NECK SEGMENT</td>
<td>51</td>
</tr>
<tr>
<td>4.4.4</td>
<td>TOE AND HAND SEGMENTS</td>
<td>51</td>
</tr>
<tr>
<td>4.5</td>
<td>ANGLE DEFINITIONS</td>
<td>52</td>
</tr>
<tr>
<td>4.6</td>
<td>SEGMENTAL PROPERTIES</td>
<td>53</td>
</tr>
<tr>
<td>4.7</td>
<td>INVERSE DYNAMICS</td>
<td>54</td>
</tr>
<tr>
<td>4.8</td>
<td>DATA REDUCTION</td>
<td>56</td>
</tr>
<tr>
<td>4.8.1</td>
<td>RUN-UP SPEED AND BALL RELEASE SPEED</td>
<td>56</td>
</tr>
<tr>
<td>4.8.2</td>
<td>FRONT LEG MOTION</td>
<td>57</td>
</tr>
<tr>
<td>4.8.3</td>
<td>MOTION OF THE BACK</td>
<td>58</td>
</tr>
<tr>
<td>4.8.4</td>
<td>POSITION OF THE BOWLING ARM</td>
<td>58</td>
</tr>
<tr>
<td>4.8.5</td>
<td>CRICKET SPECIFIC PARAMETERS</td>
<td>59</td>
</tr>
<tr>
<td>4.8.6</td>
<td>KINETIC PARAMETERS</td>
<td>60</td>
</tr>
<tr>
<td>4.9</td>
<td>STATISTICAL ANALYSIS</td>
<td>61</td>
</tr>
<tr>
<td>4.10</td>
<td>CHAPTER SUMMARY</td>
<td>62</td>
</tr>
</tbody>
</table>

### CHAPTER 5: THE FAST BOWLING ACTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>THE FAST BOWLING ACTION</td>
<td>64</td>
</tr>
<tr>
<td>5.1.1</td>
<td>THE RUN-UP AND BACK FOOT CONTACT PHASE</td>
<td>65</td>
</tr>
<tr>
<td>5.1.2</td>
<td>FRONT FOOT CONTACT PHASE</td>
<td>68</td>
</tr>
<tr>
<td>5.2</td>
<td>QUESTIONS BASED ON THE LITERATURE</td>
<td>72</td>
</tr>
<tr>
<td>5.3</td>
<td>CHAPTER SUMMARY</td>
<td>77</td>
</tr>
</tbody>
</table>

*vi*


**CHAPTER 6: RELATIONSHIPS BETWEEN FAST BOWLING TECHNIQUE AND BALL RELEASE SPEED IN CRICKET**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 ABSTRACT</td>
<td>78</td>
</tr>
<tr>
<td>6.2 INTRODUCTION</td>
<td>79</td>
</tr>
<tr>
<td>6.3 METHODOLOGY</td>
<td>80</td>
</tr>
<tr>
<td>6.3.1 PARTICIPANTS</td>
<td>80</td>
</tr>
<tr>
<td>6.3.2 DATA COLLECTION</td>
<td>81</td>
</tr>
<tr>
<td>6.3.3 DATA PROCESSING</td>
<td>82</td>
</tr>
<tr>
<td>6.3.4 KINEMATIC DATA REDUCTION</td>
<td>83</td>
</tr>
<tr>
<td>6.3.5 STATISTICAL ANALYSIS</td>
<td>85</td>
</tr>
<tr>
<td>6.4 RESULTS</td>
<td>86</td>
</tr>
<tr>
<td>6.5 DISCUSSION</td>
<td>87</td>
</tr>
<tr>
<td>6.6 CONCLUSIONS</td>
<td>90</td>
</tr>
</tbody>
</table>

**CHAPTER 7: THE EFFECT OF FRONT LEG TECHNIQUE ON PEAK GROUND REACTION FORCES IN FAST BOWLING**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 ABSTRACT</td>
<td>91</td>
</tr>
<tr>
<td>7.2 INTRODUCTION</td>
<td>92</td>
</tr>
<tr>
<td>7.3 METHODOLOGY</td>
<td>93</td>
</tr>
<tr>
<td>7.3.1 PARTICIPANTS</td>
<td>93</td>
</tr>
<tr>
<td>7.3.2 DATA COLLECTION</td>
<td>94</td>
</tr>
<tr>
<td>7.3.3 DATA PROCESSING</td>
<td>94</td>
</tr>
<tr>
<td>7.3.4 DATA REDUCTION</td>
<td>96</td>
</tr>
<tr>
<td>7.3.5 STATISTICAL ANALYSIS</td>
<td>98</td>
</tr>
<tr>
<td>7.4 RESULTS</td>
<td>98</td>
</tr>
<tr>
<td>7.5 DISCUSSION</td>
<td>101</td>
</tr>
<tr>
<td>7.6 CONCLUSIONS</td>
<td>104</td>
</tr>
</tbody>
</table>

**CHAPTER 8: DOES ‘OPTIMAL’ PERFORMANCE NECESSITATE HIGHER GROUND REACTION FORCES? A FAST BOWLING PERSPECTIVE**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 ABSTRACT</td>
<td>105</td>
</tr>
<tr>
<td>8.2 INTRODUCTION</td>
<td>106</td>
</tr>
<tr>
<td>8.3 METHODOLOGY</td>
<td>107</td>
</tr>
<tr>
<td>8.3.1 PARTICIPANTS</td>
<td>107</td>
</tr>
<tr>
<td>8.3.2 DATA COLLECTION</td>
<td>107</td>
</tr>
<tr>
<td>8.3.3 DATA PROCESSING</td>
<td>108</td>
</tr>
<tr>
<td>8.3.4 DATA REDUCTION</td>
<td>109</td>
</tr>
<tr>
<td>8.3.5 STATISTICAL ANALYSIS</td>
<td>110</td>
</tr>
<tr>
<td>8.4 RESULTS</td>
<td>111</td>
</tr>
<tr>
<td>8.5 DISCUSSION</td>
<td>113</td>
</tr>
</tbody>
</table>
CHAPTER 9: THE FORCES IN THE LOWER BACK DURING THE FRONT FOOT CONTACT PHASE OF THE FAST BOWLING ACTION

9.1 ABSTRACT
9.2 INTRODUCTION
9.3 METHODOLOGY
  9.3.1 PARTICIPANTS
  9.3.2 DATA COLLECTION
  9.3.3 DATA PROCESSING
  9.3.4 DATA REDUCTION
  9.3.5 STATISTICAL ANALYSIS
9.4 RESULTS
9.5 DISCUSSION
9.6 CONCLUSIONS

CHAPTER 10: SUMMARY AND CONCLUSIONS

10.1 THESIS SUMMARY
  10.1.1 DATA COLLECTION
  10.1.2 DATA PROCESSING
  10.1.3 DATA ANALYSIS
10.2 RESEARCH QUESTIONS
10.3 FUTURE STUDIES
10.4 CONCLUSIONS

REFERENCES

APPENDIX 1: SUBJECT DETAILS
APPENDIX 2: CONSENT FORMS
APPENDIX 3: MARKER POSITIONS
APPENDIX 4: FILTERING
APPENDIX 5: DIRECTION COSINE MATRIX
APPENDIX 6: BODYLANGUAGE CODE
| Figure 1.1  | The fast bowling action.                                      | 2  |
| Figure 2.1  | Illustrations of the four fast bowling actions at the instant of back foot contact. | 8  |
| Figure 2.2  | An illustration of the lines of the shoulder and pelvis segments at back foot contact, viewed from behind and above. | 8  |
| Figure 2.3  | Shoulder and pelvis alignment angles.                         | 9  |
| Figure 2.4  | An illustration of the front-on action and the more closed, mid-way action. | 12 |
| Figure 2.5  | The posture of a bowler early in the front foot contact phase. | 15 |
| Figure 2.6  | An illustration of the pelvis-shoulder separation angle at back foot contact. | 16 |
| Figure 2.7  | The four front knee actions: flexor, extender, flexor-extender and constant brace. | 18 |
| Figure 2.8  | Typical force trace during the back foot contact phase.       | 24 |
| Figure 2.9  | Typical force trace during the front foot contact phase.      | 24 |
| Figure 2.10 | The motion of the front knee during the front foot contact phase. | 26 |
| Figure 2.11 | A bowler at the instant of ball release.                      | 32 |
| Figure 3.1  | The data collection environment.                              | 34 |
| Figure 3.2  | Images obtained from the two high-speed video cameras.        | 36 |
| Figure 3.3  | An illustration of the positions of the forty-seven markers used. | 37 |
| Figure 3.4  | Illustration of the ball marker.                             | 37 |
| Figure 3.5  | Illustration of the initial trials recorded: static and range of motion. | 38 |
| Figure 3.6  | A graph of the change in distance between the marker on the ball and the mid-point of the markers on the wrist. | 40 |
| Figure 3.7  | Example of the filling of a small gap in a trajectory using open “spline fill”. | 41 |
| Figure 3.8  | Illustration of a gap filled using a dummy reference frame.   | 42 |
| Figure 3.9  | Illustration of a gap filled using the “copy trajectory” function. | 42 |
| Figure 3.10 | Illustration of the method used to identify an appropriate cut-off frequency. | 43 |
| Figure 4.1  | Illustration of the 18 segment representation of the human body. | 45 |
Figure 4.2  Illustration of the sections of the spine.  
Figure 4.3  Illustration of the orientation of the 18 segments’ coordinate axes.  
Figure 4.4  The kinetic hierarchy used in the inverse dynamics calculations.  
Figure 4.5  Diagram showing direction of positive forces and moments.  
Figure 4.6  An illustration of the calculation of the plant angle, foot-strike and stride length.  
Figure 4.7  The measured shoulder angle at release and ball release height.  
Figure 4.8  Illustrations of the projection angle of the shoulder and pelvis at back foot contact and the lean back angle.  
Figure 4.9  An illustration of the oscillations observed in the flexion-extension moment of the front knee for filtered and unfiltered analogue data.  
Figure 5.1  The fast bowling action.  
Figure 5.2  An illustration of the shoulder alignment angle at back foot contact for the most side-on bowler and the most front-on bowler in this study.  
Figure 5.3  An illustration of the pelvis-shoulder separation angle at back foot contact.  
Figure 5.4  Illustration of a bowler counter-rotating their shoulders and extending their front leg during the back foot contact phase.  
Figure 5.5  The front leg techniques.  
Figure 5.6  An illustration showing the bowlers with the most dorsi-flexed and most plantar-flexed foot at the instant of front foot contact.  
Figure 5.7  The posture of a bowler early in the front foot contact phase.  
Figure 5.8  The position of the bowling arm at ball release.  
Figure 6.1  The data collection environment.  
Figure 6.2  The marker positions used in this study.  
Figure 6.3  Illustration of the shoulder angle calculated at ball release.  
Figure 6.4  The pelvis and shoulder projection angles for a bowler at back foot contact.  
Figure 7.1  The marker positions used in this study.  
Figure 7.2  The eighteen local coordinate systems representing the full body.  
Figure 7.3  An illustration of the foot-strike indicator and plant angle.  
Figure 7.4  A typical ground reaction force trace during the front foot contact phase.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>An illustration of the resultant ground reaction force during the initial part of the front foot contact phase.</td>
<td>102</td>
</tr>
<tr>
<td>8.1</td>
<td>The marker positions used in this study.</td>
<td>108</td>
</tr>
<tr>
<td>8.2</td>
<td>A typical ground reaction force trace during front foot contact.</td>
<td>109</td>
</tr>
<tr>
<td>8.3</td>
<td>An illustration of the calculated plant angle.</td>
<td>110</td>
</tr>
<tr>
<td>9.1</td>
<td>The marker positions used in this study.</td>
<td>119</td>
</tr>
<tr>
<td>9.2</td>
<td>The eighteen local coordinate systems representing the full body.</td>
<td>121</td>
</tr>
<tr>
<td>9.3</td>
<td>The kinetic hierarchy used in this study.</td>
<td>122</td>
</tr>
<tr>
<td>9.4</td>
<td>An illustration of the foot-strike indicator and the plant angle.</td>
<td>123</td>
</tr>
<tr>
<td>9.5</td>
<td>An illustration of the peak resultant forces at the ground and those calculated in the lower back using inverse dynamics.</td>
<td>124</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

Table 2.1  Mean peak forces for the back and front foot contact phases of the fast bowling action.  
Table 2.2  Peak impact loading rates (PILR) and peak vertical loading rates (PVLR).  
Table 4.1  Details of the joint angles calculated.  
Table 4.2  Details of the assumptions made regarding the correspondence of the levels of the geometric model of Yeadon (1990) and the joint centres defined in this study.  
Table 4.3  Comparison of the moments calculated at the ankle, knee and hip for a static balance using inverse dynamics and quasi-statics.  
Table 5.1  Correlations between ground reaction force characteristics and parameters describing the motion of the front knee during the front foot contact phase.  
Table 6.1  Details of the range, mean and standard deviation of each technique parameter calculated for the group of bowlers.  
Table 6.2  Details of the predictive equations produced using linear regression to explain ball release speed.  
Table 7.1  Details of the range, mean and standard deviation of each technique parameter for the group of bowlers.  
Table 7.2  Details of the range of values obtained for each kinetic parameter.  
Table 7.3  Details of the best predictive equations produced for peak vertical force using linear regression.  
Table 7.4  The parameters that best explain the variation in peak breaking force.  
Table 7.5  Details of variables used to explain the time to peak vertical force.  
Table 7.6  Details of variables used to explain the time to peak braking force.  
Table 8.1  Details of the range of values obtained for each kinetic parameter.  
Table 8.2  Details of the range, mean and standard deviation of each kinematic parameter calculated for the group of bowlers.  
Table 8.3  Correlations between kinetic parameters and ball release speed.  
Table 8.4  Correlations between ball release speed, breaking impulse and parameters describing the kinematics of bowling technique.
Table 9.1  Details of the range, mean and standard deviation for each calculated parameter.  125

Table 9.2  Details of the predictive equations obtained explaining the variation in peak resultant lower back force when the peak resultant ground reaction force was used as an input parameter.  126

Table 9.3  Details of the predictive equations obtained explaining the variation in peak resultant lower back force when only kinematic technique parameters were used.  127
This chapter will provide details of the motivation for this thesis and an outline of the previous research conducted in this area. The purpose of the study is explained and research questions are posed with reference to the literature. Lastly, an overview of this thesis is provided with a brief description of each chapter.

1.1 THE AREA OF STUDY

The game of cricket can be described simply as a contest between bowlers, who deliver the ball, and batsmen who try to score runs by hitting the ball. Within a cricket team there can be both fast bowlers (who deliver the ball at around 39 – 43 m.s\(^{-1}\)) and spin bowlers (who can be one of two types: off-spin or leg-spin).

Fast bowling is a dynamic activity requiring bowlers to run-up and repeatedly deliver the ball at high speeds (Figure 1.1). Ball release speed is a major contributor to fast bowling success as it reduces the time the batsman has to interpret the path of the ball and make decisions regarding which shot to play. In international matches, bowlers may perform as many as 180 deliveries a day. Although cricket is generally considered a low-injury sport, fast bowlers have injury rates comparable to contact sports such as Australian rules football and the Rugby football codes (Orchard \textit{et al.}, 2006). Lower back injury is the most prevalent injury among fast bowlers, with lumbar stress fractures which occur predominantly on the non-dominant (non-bowling arm) side accounting for the most lost training and playing time (Gregory \textit{et al.}, 2004).
The rationale for this research study is to analyse the fast bowling action to gain an understanding of the effect of interactions between aspects of fast bowling technique on ball release speed and the forces exerted on the bowler. While previous research has looked to identify links between fast bowling technique and ball release speed, none have considered the effects of interactions between elements of technique. Some studies have considered the contribution of run-up length or run-up speed (Davis and Blanksby, 1976a; Elliott et al., 1986) on release speeds. Others have considered individual aspects of front leg technique (Elliott et al., 1986; Burden and Bartlett, 1990b; Portus et al., 2004), the motion of the thorax (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1990a; Portus et al., 2004), or the position of the arm at ball release (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1989; Foster et al., 1989; Burden, 1990). There is currently no consensus regarding the effect of these elements of technique on ball
release speed, it seems likely that these contradictory results may be due to interactions between technique variables which have not been addressed.

A number of studies have reported ground reaction forces during the front foot contact phase of the bowling action (Elliott et al., 1986, 1992, 1993; Foster et al., 1989; Mason et al., 1989; Saunders and Coleman, 1991; Hurrion et al., 1997a, 1997b, 2000; Portus et al., 2004). However, no studies have considered these forces in conjunction with three-dimensional kinematic data of the bowling action. Currently, no studies have attempted to calculate the forces experienced in the lower back of fast bowlers.

A three-dimensional inverse-dynamics analysis of the fast bowling action has the potential to provide a more thorough understanding of the mechanics of fast bowling, in addition to the effect of technique on ground reaction forces and loading in the lower back. This will allow current coaching practises to be better informed and also help identify those bowlers who are likely to have higher forces in their back and may be at higher risk of injury.

1.2 STATEMENT OF PURPOSE

Full-body three-dimensional kinematics and ground reaction force characteristics will be calculated to enable the analysis of fast bowling techniques. In particular, the effect of interactions between aspects of fast bowling technique on ball release speed and ground reaction forces. A full-body inverse-dynamics analysis will be developed, enabling forces in the lower back to be estimated and their link with bowling technique to be addressed.

The fast bowlers will be represented as a system of 18 rigid segments linked by pin joints. Kinematic, kinetic and anthropometric data will be collected for a group of 20 elite fast bowlers. The analysis will be customised for each bowler, using subject-specific segmental parameters determined using the geometric model of Yeadon (1990). The inverse-dynamics analysis will be used to calculate parameters describing elements of fast bowling technique as well as characteristics of the ground reaction forces and the forces in the lower back.

The output from the analysis will be used to address correlations between technique, ball speed and ground reaction forces which have previously been reported / proposed in the literature. The interactions between aspects of fast bowling technique which determine
ball release speed will be identified. The effect of front leg technique on ground reaction forces and forces in the lower back, during the front foot contact phase of the bowling action, will also be addressed.

1.3 RESEARCH QUESTIONS

1. Which aspects of fast bowling technique characterise the fastest bowlers?

Ball release speed is a major contributor to fast bowling success and has been the focus of a number of previous investigations. These studies have identified individual aspects of fast bowling technique which characterise the fastest bowlers. However, none have accounted for the interactions between technique variables. The analysis performed will enable those aspects of technique which best characterise the fastest bowlers to be identified and the mechanics by which bowlers generate pace to be more thoroughly understood.

2. What is the effect of the front leg technique used by fast bowlers on the ground reaction forces during the front foot contact phase?

Fast bowlers exhibit a variety of peak ground reaction forces during the front foot contact phase of the bowling action. It has been suggested that bowlers with a more extended front knee at front foot contact, or those who extend their knee more from this instant until ball release, experience higher peak forces and loading rates (Portus et al., 2004). No previous studies have combined kinetic data for the front foot contact phase of the bowling action with high frequency three-dimensional footage of the action. The analysis performed will allow the associations between front leg kinematics and ground reaction forces to be investigated more thoroughly.

3. Do the fastest bowlers have the highest peak ground reaction forces and loading rates?

Previous researchers have suggested large peak ground reaction forces during the front foot contact phase, together with lateral flexion, hyperextension and rotation of the lower back, could be a major cause of lower back injuries to fast bowlers (Bartlett et al., 1996; Ranson
et al., 2008). A fundamental issue to address, therefore, is whether these high forces are unavoidable if a bowler is to release the ball at high speeds. The analysis performed will enable relationships between ground reaction forces and ball release speed to be addressed.

4. What is the effect of the front leg technique used and the ground reaction forces on the peak forces in the lower back during the front foot contact phase of the bowling action?

Previous research has assumed that those bowlers with the highest ground reaction forces will be at the greatest risk of lower back injury. However, no study has calculated the forces that are acting in the back. The inverse dynamics calculations performed will enable the effect of the motion of the front leg during the front foot contact phase on peak forces in the back to be investigated.

1.4 CHAPTER ORGANISATION

Chapter 2 provides a review of the research conducted into fast bowling in cricket. An overview of fast bowling terminology and current action classification systems are provided. Research into links between aspects of bowling technique and the occurrence of lower back injury has been the most common focus of fast bowling research, these studies are discussed and proposed injury mechanisms outlined. Previous investigations into associations between bowling technique, ground reaction forces and ball release speed are also reviewed.

Chapter 3 describes the equipment and protocols used to collect the kinematic, kinetic and anthropometric data. Details are provided regarding the participants, equipment used and the specific data collected. The methods used to fill gaps in the kinematic data and the filtering performed are also explained.

Chapter 4 provides details of the three-dimensional inverse-dynamics analysis developed to analyse the fast bowling action. The number of segments used to represent the bowler are justified and the methodology used to define each segment explained. The calculation of technique parameters are defined and details of the statistical tests performed on the data described.
Chapter 5 outlines the key elements of the fast bowling action and provides details of the techniques used by the twenty subjects participating in this study. A number of reported / proposed relationships between bowling technique, ball speed and ground reaction forces are addressed using simple statistical analyses.

Chapters 6 – 9 are written in the form of papers and address the four research questions posed. Chapters 6 and 7 use linear regression to address relationships between bowling technique and: ball release speed; and characteristics of ground reaction forces. Chapter 8 considers relationships between ground reaction force characteristics and ball release speed by means of correlations. Chapter 9 uses inverse-dynamics to estimate the forces in the lower back of fast bowlers and uses linear regression to identify relationships with ground reaction forces and bowling technique.

Chapter 10 summarises the methods used in this study and identifies the limitations. The research questions posed in Chapter 1 are addressed and potential future studies are proposed.
Lower back injuries to fast bowlers are the most prevalent injuries in international cricket, consequently they have been the focus of a number of previous published studies. In this chapter, the current methodology used to classify fast bowling actions is outlined and commonly used terminology defined. Reported links between bowling technique and lower back injury are discussed and an overview of the proposed injury mechanisms is provided. The chapter concludes by discussing relationships between aspects of fast bowling technique and both ground reaction forces and ball release speed.

2.1  ACTION CLASSIFICATION AND TERMINOLOGY

Fast bowling action classification systems were originally designed to broadly describe bowling technique and the biomechanical factors affecting performance (Elliott and Foster, 1984; Elliott et al., 1986). These classification systems have since been modified and used in an attempt to identify fast bowlers at particular risk of developing lower back injury (Burnett et al., 1996; Foster et al., 1989; Portus et al., 2004). This section will focus on the fast bowling classification system used in recent research within the cricket governing bodies of the United Kingdom and Australia.

Fast bowling actions are commonly categorised as one of four types: front-on, side-on, mid-way and mixed (Figure 2.1). Actions are classified according to the alignment of the shoulders at back foot contact (BFC), the amount of shoulder counter-rotation (SCR) occurring during the delivery stride and the pelvis-shoulder separation angle at back foot contact (Portus et al., 2004). Fast bowling actions have traditionally been classified using a video camera placed overhead, viewing the bowler in the transverse plane (Foster et al., 1989; Elliott et al., 1992; Burnett et al., 1995, 1996). A very similar methodology is still in use today (Figure 2.2). The lines of the pelvis and shoulder segments are defined to be the line joining their respective joint centres (Portus et al., 2004).
Figure 2.1 – Illustrations of the four fast bowling actions at the instant of back foot contact: (A) side-on; (B) mid-way; (C) front-on; (D) two examples of a mixed action. Notice that in (A), (B) and (C) the shoulders and pelvis are in line, whereas in (D) they are not (adapted from Portus et al., 2004).

Figure 2.2 – An illustration of the lines of the shoulder and pelvis segments at back foot contact, viewed from: (A) behind; and (B) above.
The zero line is defined to run directly down the wicket from the rear hip and shoulder, with the alignment angle measured in an anti-clockwise direction for right-handers (Portus et al., 2004). The amount of shoulder counter-rotation is defined as the difference between the shoulder angle at back foot contact and the smallest (most side-on) shoulder angle achieved during the delivery stride. The pelvis-shoulder separation angle is calculated at back foot contact by subtracting the pelvis alignment angle from the shoulder alignment. A positive separation angle corresponds to the shoulders being in a more front-on alignment than the pelvis segment.

(A)  
(B)  

Figure 2.3 – Shoulder and pelvis alignment angles. (A) and (B) show a bowler with a shoulder (and pelvis) alignment of 180° and 240°, respectively (adapted from Bartlett et al., 1996).

The fast bowling classification system recently used within the cricket associations of the United Kingdom (Ranson et al., 2008) and Australia (Portus et al., 2004) is:

**Side-on:**

Shoulder alignment angle at BFC < 210°

And pelvis-shoulder separation angle at BFC < 30°

And SCR < 30°

**Mid-way:**

210° ≤ shoulder alignment angle at BFC ≤ 240°

And pelvis-shoulder separation angle at BFC < 30°

And SCR < 30°
**Front-on:**

shoulder alignment angle at BFC > 240°

And

pelvis-shoulder separation angle at BFC < 30°

And

SCR < 30°

**Mixed:**

pelvis-shoulder separation angle at BFC ≥ 30°

And / Or

SCR ≥ 30°

The definitions used to classify actions have varied over the years. Some investigations have not included the mid-way technique (Elliott *et al.*, 1992) and the range of shoulder angles corresponding to each action classification have varied. Similarly, the shoulder counter-rotation thresholds defining a mixed action have ranged from as low as 10° (Elliott *et al.*, 1992) to as high as 40° (Foster *et al.*, 1989). Portus *et al.* (2004) found the pelvis-shoulder separation angle at back foot contact was not associated with pars interarticularis stress injury in fast bowlers. Consequently, one of the most recent studies conducted, Ranson *et al.* (2008), identified mixed action bowlers based solely on the amount of shoulder counter-rotation they exhibited.

There has been criticism of a lack of consistency in the research conducted by different research groups, in particular: the sampling rate; the definition of back foot contact or impact; thorax alignment; and the choice of anatomical locations used to define the shoulder and pelvis segments (Portus *et al.*, 2004). Ranson *et al.* (2008) looked to quantify the effect of using different definitions of back foot contact (initial back foot contact and back foot flat) on the calculated amount of shoulder counter-rotation and action classification. Unsurprisingly, they found measuring shoulder alignment at back foot impact resulted in a higher mean shoulder counter-rotation than when the later, back foot flat definition was used (41° vs. 34°).
2.2 LOWER BACK INJURIES IN FAST BOWLING

During the early 1980s, lower back injuries in fast bowlers were attributed to the inability of bowlers to achieve a side-on orientation during the delivery stride (Elliott, 2000). Early research conducted by Elliott et al. (1986) and Foster et al. (1989) suggested that a trend among players towards a more front-on alignment of the shoulders at back foot contact was a contributory factor in the apparent increased occurrence of lower back injuries. It is now believed that the development of lower back injury in fast bowlers is multi-factorial, involving: incorrect technique; poor preparation; overuse and clinical features (Bell, 1992; as cited by Elliott et al., 1995). However, technique has been the predominant area of research due to reported relationships between specific aspects of technique and the appearance of radiological abnormalities of the lower back (Burnett et al., 1996; Elliott et al., 1992, 1993).

Foster et al. (1989), in a study of 82 high performance young male fast bowlers (mean age 16.8 years), were the first researchers to statistically link increased incidence of lower back injury with specific aspects of bowling kinematics. Both the amount of shoulder counter-rotation and the ball release height (as an absolute value or a percentage of standing height) were found to be significantly related to the incidence of bony injury to a vertebra in the lower back (P < 0.05). Subsequent research has supported these findings. Elliott et al. (1992), in a study of 20 members of the Western Australian fast bowling development squad (mean age 17.9 years) also found significant relationships between the occurrence of abnormal bony radiographic features and both the amount of shoulder counter-rotation and ball release height (P < 0.05). Similarly, Elliott et al. (1993) found a relationship between shoulder counter-rotation and abnormal intervertebral disc features in a group of 24 male fast bowlers competing at school and club level (mean age 13.7 years). The work of Portus et al. (2004) further supports the existence of a relationship between shoulder counter-rotation and lower back injury.

The alignment of the shoulders at back foot contact has been strongly correlated with shoulder counter-rotation (Portus et al., 2000; Portus et al., 2004). Bowlers landing with a more front-on alignment counter-rotate their shoulders more than those with a more closed shoulder orientation at back foot contact (Figure 2.4). Portus et al. (2004) emphasised that bowlers using both the front-on and the more closed techniques (mid-way and side-on) rarely execute these techniques properly – not remaining front-on throughout the delivery
stride and not aligning the shoulders and pelvis at back foot contact, in the two cases respectively. Both these common faults in executing the fast bowling action can lead to excessive shoulder counter-rotation.

(A)

(B)

**Figure 2.4** – An illustration of: (A) the front-on action; and (B) the more closed, mid-way action.

Elliott and Khangure (2002) conducted an intervention study involving 41 young males from the Western Australian Cricket Association fast bowling development squad over a period of 2-3 years (mean age 13.3 years at the start of the study). Bowlers attended an annual half day clinic and six small group coaching sessions spread over the season, aimed at assisting the bowlers to develop the front-on or side-on bowling technique. The amount of shoulder counter-rotation was found to decrease significantly over the period; the
incidence and progression of lumbar disc degeneration were reduced in parallel with the reduction in shoulder counter-rotation (P < 0.01).

Among coaches it is often suggested that higher ball release speeds are attained when technique is smooth and rhythmical as opposed to an extreme effort to bowl fast. The latter may lead a bowler to subconsciously increase their shoulder counter-rotation (Portus et al., 2004). Burnett et al. (1995) investigated changes in the amount of shoulder counter-rotation exhibited by bowlers over the course of a 12-over spell, they found no significant changes in the general technique occurred over the duration of the spell. However, when the subjects were grouped according to their action type, there was evidence of a tendency for front-on bowlers to increase their shoulder counter-rotation. Burnett et al. (1995) concluded that the effect of changes in the shoulder counter-rotation of bowlers on spinal mechanics as they bowl extended spells is difficult to assess. Information such as the movement of the lumbar vertebrae during the shoulder counter-rotation in relation to each lumbar vertebra’s range of motion would need to be considered (Stokes, 1988, as cited by Burnett et al., 1995).

Although fast bowling action classification schemes have varied over the years and between research groups, all have classified bowlers with excessive shoulder counter-rotation as having a mixed action. The exact value used to define “excessive” has varied as mentioned in Section 2.1. This link between the mixed action and lower back injury is of particular concern as recent studies, including: Elliott and Khangure (2002); Portus et al. (2004); and Ranson et al. (2008), have found the mixed technique to be the most prevalent among fast bowlers, being used by up to 78% of elite fast bowlers.

The Marylebone Cricket Club (MCC) Coaching Book only acknowledged the front-on technique in 1994 (Bartlett, 2003). Previously, the side-on technique was the only recognised bowling style. This has possibly contributed to the high incidence of mixed action bowlers, as coaches tried to convert front-on bowlers into side-on bowlers, but instead made them mixed (Bartlett, 2003). More recently, cricketing authorities have attempted to reduce the incidence of lower back injuries. The England and Wales Cricket Board (ECB), for example, in recent years has provided coaches with information on how to coach the front-on technique, how to recognise the mixed technique and how to convert the latter technique into the side-on or front-on technique (Bartlett, 2003).
Other aspects of fast bowling technique that have been suggested as being related to lower back injury occurrence include: the knee and hip angles during the front foot contact phase; and the pelvis-shoulder separation angle during the delivery stride. Portus et al. (2004) collected data from a group of 42 high performance male fast bowlers (mean age 22.4 years) over a four year period. They found players with lower back stress fractures to have larger hip angles at front foot contact and ball release, whereas non injured bowlers had a more flexed front knee at ball release. The same researchers found bowlers with a back injury to have a larger pelvis-shoulder separation angle at back foot contact. However, none of these findings were statistically significant.

The following section provides details of the mechanisms that have been proposed in the literature to explain the links between lower back injury and aspects of fast bowling technique. These factors are: shoulder counter-rotation; pelvis-shoulder separation angle; front leg kinematics; physical capacities; and overuse.

### 2.2.1 SHOULDER COUNTER-ROTATION

The link between lower back injury and excessive shoulder counter-rotation (i.e. a mixed action) is the most widely reported relationship between technique and injury in fast bowlers (Foster et al., 1989; Hardcastle et al., 1992; Elliott et al., 1992, 1993; Burnett et al., 1996; Portus et al., 2004). Portus et al. (2004) proposed that the injury mechanism may be more than just the twisting of the spine during this movement. They identified a predisposition of bowlers with large amounts of shoulder counter-rotation to adopt a hyperlordotic or laterally flexed posture at front foot contact (Figure 2.5). The adoption of this position coincides with large ground reaction forces being exerted on the front leg (Burnett et al., 1998). Similarly, Foster et al. (1989) concluded that the repetitive lateral flexion of the trunk and the hyperlordotic posture adopted by front-on bowlers (typically exhibiting large amounts of shoulder counter-rotation) during the delivery stride would increase the possibility of developing a lumbar stress fracture.
It is generally accepted that lower-back stress fractures are common in sports requiring repeated episodes of combined trunk rotation and hyperextension (Brukner and Khan, 1997; as cited by Portus et al., 2004). When bowling, the ground reaction forces generated during front foot contact are transmitted via the bones, tendons and muscles to the knee and hip joints and absorbed by the body (Nigg, 1992; as cited by Foster et al., 1989). If the spine is erect, the intervertebral compressive forces developed during front foot contact are more likely to be resisted by the bowler’s intervertebral discs. However, in a lordotic posture or when the spine is hyper-extended, the facet joints may bear more of this compressive force (Foster et al., 1989). Links between shoulder counter-rotation, the adoption of a lordotic posture during front foot contact and lower back injuries are one of the main areas of recent work. A comprehensive review of this research is the focus of Section 2.2.5.

2.2.2 PELVIS-SHOULDER SEPARATION ANGLE

Stockill and Bartlett (1992a) proposed that the pelvis-shoulder separation angle in the transverse plane should be considered when analysing injury mechanisms of the lower back in fast bowlers (Figure 2.6). The reasoning being that the lumbar spine lies between the hip and shoulder girdles. Furthermore, the pelvis-shoulder separation angle has been
used in the analysis of many athletic throwing events such as discus, hammer and javelin, in an attempt to determine the optimal technique for propelling the implement in the most effective way (e.g. Bartlett, 1992).

![Figure 2.6](image)

**Figure 2.6** – An illustration of the pelvis-shoulder separation angle at back foot contact.

Foster *et al.* (1989) suggested that a properly timed summation of the segmental velocities of the shoulders and pelvis was important in reducing stress in the lumbar region. These conclusions were supported by Portus *et al.* (2004) who found a well timed pelvis-shoulder segmental summation was important to generate a positive maximum pelvis-shoulder separation angle closer to ball release (after front foot contact) both to reduce injury risk and increase ball release speed.

Burnett *et al.* (1995) found that bowlers using the mixed action, in addition to having a large amount of trunk twisting occurring during the shoulder counter-rotation, also had more twist at release (greater pelvis-shoulder separation angle). This is of some concern as the trunk becomes increasingly flexed after release. Pearcy (1993; as cited by Burnett *et al.*, 1995) suggested that there may be a mechanism for increased vulnerability of the posterior annulus to injury when twisting is combined with flexion.

Portus *et al.* (2004) found the pelvis-shoulder separation angle at back foot contact to be similar for both injured and non-injured players. They also found no significant difference in the pelvis-shoulder separation angle at any time in the delivery stride between the two
groups. The differentiating factor between the two groups was instead the amount of shoulder counter-rotation occurring after back foot contact. This may indicate that in everyday high-performance coaching environments where an overhead camera can be used, the quantification of shoulder counter-rotation alone to indicate the torsion experienced in the trunk is sufficient.

2.2.3 FRONT LEG KINEMATICS

The role of the front lower limb (leg) has been implicated as a mechanistic factor in the development of lower back injury (Foster et al., 1989; Mason et al., 1989, as cited by Portus et al., 2004). Portus et al. (2004) introduced a new system for classifying the front knee action used by bowlers during the period from front foot flat (the instant the forefoot strikes the ground) until ball release, consisting of four techniques: flexor; extender; flexor-extender; and constant brace. These techniques were defined as:

**Flexor** – knee flexion 10° of more followed by less than 10° of knee flexion (Figure 2.7A).

**Extender** - knee flexion of less than 10° followed by knee extension of 10° or more (Figure 2.7B).

**Flexor-Extender** – flexion and extension of the knee by 10° or more (Figure 2.7C).

**Constant brace** – both flexion and extension of the knee less than 10° (Figure 2.7D).
Figure 2.7 – The four front knee actions: (A) Flexor; (B) Extender; (C) Flexor-Extender; (D) Constant brace.
In a group of 42 high performance male fast bowlers, Portus et al. (2004) found flexors (25/42) to be the most common, followed by constant brace (9/42). It has been proposed that the ideal front leg technique is one in which the knee flexes initially to help attenuate impact forces, and then extends before ball release to enable increased delivery speeds (Bartlett et al., 1996). The relationships between front leg kinematics and the ground reaction forces are discussed in detail in Section 2.3.

### 2.2.4 OTHER FACTORS

Foster et al. (1989) found bowlers with a low longitudinal foot arch were significantly more likely to develop stress fractures in the lower back than bowlers with a normal or high arch (P < 0.05). It was suggested that a foot with a low arch may not be as capable of absorbing the large ground reaction forces generated during the fast bowling action. Subsequent research by Elliott et al. (1992) did not support these findings.

Mackay and Keech (1988, as cited by Elliott et al., 1992) showed that tightness in muscle groups surrounding the pelvis may increase lumbar lordosis – curvature of a section of the spine. This may predispose fast bowlers to both bony and intervertebral abnormalities (Ogilvie and Sherman, 1987; Wiltse, 1971; as cited by Elliott et al., 1992). Elliott et al. (1992) found bowlers with lower back injuries had significantly less hamstring flexibility than non-injured bowlers. However, they warned that this may be as a consequence of the injury rather than its cause.

Overuse has been implicated in the development of lower back injury in fast bowlers and there is increasing evidence to support this theory (Foster et al., 1989; Dennis et al., 2003, 2005; as cited by Ranson et al., 2008). Foster et al. (1989) reported that 59% of bowlers (in comparison to 38% for the entire group) who bowled in more than the mean number of matches suffered a lower back injury. Similarly, Dennis et al. (2003) observed that bowlers who averaged less than two days between bowling sessions, or bowled more than an average of 188 deliveries a week, were significantly more likely to develop lower back injuries than those who bowled less deliveries or less frequently.
2.2.5 THREE-DIMENSIONAL KINEMATICS DURING FRONT FOOT CONTACT

This section focuses specifically on the three-dimensional kinematics of the lower back during the front foot contact phase. In particular, how the combined motion of the spine in conjunction with large ground reaction forces may be related to the development of injuries in the lower back. Chosa et al. (2004) found unilateral pars interarticularis stress to be greatest under combinations of compression with lumbar extension, compression with lumbar side-flexion to the same side and compression with lumbar rotation to the opposite side. The current fast bowling action classification system uses variables measured between back foot contact and front foot contact. During this period, the lower trunk is typically positioned in a relatively neutral posture compared to that during the period from front foot contact to ball release. This neutral posture, in addition to the front (contralateral) foot not being in contact with the ground, means there is likely to be relatively little stress on the contralateral side lumbar pars interarticularis during the back foot contact phase of the bowling action (Ranson et al., 2008).

Burnett et al. (1998) investigated aspects of the three-dimensional kinematics of the lower back using an electromagnetic device (3-Space®Fastrak™) operating at 120 Hz. They concluded that the movements most likely to place the greatest mechanical load on the lumbar spine occur between front foot contact and ball release. These movements coincide with the phase of the bowling action during which peak ground reaction forces are produced (Elliott et al., 1986; Foster et al., 1989; Hurrion et al., 2000).

Ferdinands et al. (2009) developed a fifteen segment three-dimensional inverse-dynamics model of a fast bowler and used this to investigate and identify the magnitude and temporal characteristics of the lumbar spine kinetics during the bowling action. They observed that the lumbar spine segment was subjected to very high loading during the bowling action, particularly during the front foot contact phase.

Ranson et al. (2008), who collected three-dimensional kinematic data using a Vicon Motion Analysis System (Oxford, UK), confirmed these lower trunk movements known to produce high contralateral facet joint contact forces (i.e. lower trunk extension, contralateral side-flexion, and ipsilateral rotation (Chosa et al., 2004)), typically peaked just after the instant of front foot contact. The combination of large facet joint contact forces and high compressive forces occurring around front foot contact produces high
stress in the contralateral posterior bony elements of the lumbar spine (Chosa et al., 2004; De Visser et al., 2007). When repeated in high volume, as is the case for professional fast bowlers, it has been speculated that this mechanism may provide the aetiology for the high rate of contralateral side lumbar bony stress lesions observed in elite fast bowlers (Elliott et al., 1992; Gregory et al., 2004; Ranson et al., 2005).

Ranson et al. (2008) compared the maximum amount of extension, contralateral side-flexion and ipsilateral rotation of the lower trunk in the bowling action, with maximum values obtained in a standing range of motion trial. They found a surprisingly large amount of contralateral side-flexion occurred around front foot contact (129% of value obtained in range of motion trial). This coincided with a phase of the bowling action in which the lower trunk is also extended and rotated to the ipsilateral side. These coupled movements should have reduced the range of available side-flexion (Burnett et al., 2008). In comparison, the maximum amount of extension and ipsilateral rotation used during the front foot contact phase was 26% and 79% respectively.

From the perspective of trying to distinguish bowlers who are at greater risk of developing injuries to the lower trunk, it is necessary to identify certain aspects of technique which appear to be linked to the development of injury. Previously, the mixed action has been associated with greater risk of injury. However, both Ranson et al. (2008) and Burnett et al. (1998) found no significant difference in the lower trunk kinematics of mixed and non-mixed action bowlers.

On examining effect sizes, both groups of researchers observed a non-significant trend towards mixed action bowlers having a greater magnitude of contralateral lower trunk side-flexion. It should be noted that Ranson et al. (2008) only observed this medium effect size (and a similar one for ipsilateral rotation) when using their back foot impact definition of back foot contact (i.e. not when they used “back foot flat” as their definition of the instant of back foot contact). Only a small effect size was observed for extension when using the back foot impact definition and for all lower trunk kinematic variables when using the back foot flat definition.

Ranson et al. (2008) concluded that although the contralateral side-flexion and ipsilateral rotation results were close to statistical significance, when examined with the results of Burnett et al. (1998) in mind, they cannot conclusively support the notion that bowlers with high shoulder counter-rotation (i.e. mixed action bowlers) tend to use a greater
proportion of available lower trunk range of motion during the delivery stride of fast bowling.

Ranson et al. (2008) proposed that concurrent lower trunk extension, ipsilateral rotation and extreme contralateral side-flexion during the early part of the front foot contact phase of the bowling action may be an important mechanical factor in the aetiology of this type of injury. However, they highlighted the need for further prospective and mechanical modelling studies to determine the relationship between lower back kinematics, variables previously found to be related to back injury (e.g. shoulder counter-rotation), and lumbar spine stress injuries in fast bowlers.

2.3 KINETICS OF FAST BOWLING

Research into ground reaction forces has focussed on the front foot contact phase, as the forces are typically far higher than during back foot contact. Table 2.1 provides a summary of the research into the ground reaction forces occurring during the delivery stride.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Subjects</th>
<th>Mean Approach Speed (ms$^{-1}$)</th>
<th>Back Foot Contact (BW)</th>
<th>Front Foot Contact (BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliott and Foster (1984)</td>
<td>4 international seniors</td>
<td>4.3 ± 0.3</td>
<td>4.7 ± 0.4</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>Foster and Elliott (1985)</td>
<td>1 international senior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elliott et al. (1986)</td>
<td>15 elite seniors</td>
<td></td>
<td>3.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Foster et al. (1989)</td>
<td>82 juniors (age 16.8yrs)</td>
<td>4.95 ± 1.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mason et al. (1989)</td>
<td>15 fast-medium juniors</td>
<td></td>
<td>5.43</td>
<td>2.45</td>
</tr>
<tr>
<td>Saunders and Coleman (1991)</td>
<td>7 fast-medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elliott et al. (1992)</td>
<td>20 juniors (age 17.9yrs)</td>
<td>2.9 ± 0.8</td>
<td>6.4 ± 1.1</td>
<td>1.9 ± 1.2</td>
</tr>
<tr>
<td>Elliott et al. (1993)</td>
<td>24 juniors (age 13.7yrs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Group 1</td>
<td></td>
<td>4.8 ± 1.4</td>
<td>2.1 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Group 2</td>
<td></td>
<td>5.2 ± 0.9</td>
<td>2.6 ± 0.7</td>
</tr>
</tbody>
</table>
Hurrion et al. (1997a)  
6 fast-medium (indoors)  
5.48 ± 1.08  
2.17 ± 0.81

Hurrion et al. (1997b)  
6 fast-medium (outdoors)  
4.84 ± 0.24  
5.32 ± 1.40  
2.47 ± 1.05

Hurrion et al. (2000)  
6 fast-medium (outdoors)  
5.67 ± 0.27  
2.37 ± 0.14  
0.94 ± 0.16  
5.75 ± 0.98  
3.54 ± 0.67

Table 2.1 – Mean peak forces for the back and front foot contact phases of the fast bowling action (adapted from Hurrion et al., 2000).

During the back foot contact phase of the bowling action, reported peak vertical and braking forces range from 2.0-2.9 body-weights (BW) and 0.94-1.1 BW, respectively. The studies of Mason et al. (1989), Saunders and Coleman (1991) and Elliott et al. (1992), measured ground reaction forces during back and front foot contact in separate trials; bowlers adjusted the starting position of their run-up such that a particular foot strike was on the force plate. Hurrion et al. (2000) were the first researchers to publish force data collected simultaneously for both front and back foot contact; using a specially designed force plate rig enabling two pietzoelectric force plates (500 Hz) to be positioned appropriately for each bowler.

In the literature, reported mean peak vertical and horizontal ground reaction forces during the front foot contact phase are in the range 3.8-9.0 BW and 1.4-4.5 BW, respectively. The most recent studies, Hurrion et al. (2000) and Portus et al. (2004), observed higher peak braking forces than reported previously (3.54 and 4.5 BW, respectively). Hurrion et al. (2000) suggested a higher approach speed, bowling technique, or the commitment and ease with which bowlers were able to bowl within the confines of the testing procedure may be possible explanations. Typical force traces for the back and front foot contact phases of the bowling action are shown in Figures 2.8 and 2.9.
Figure 2.8 – Typical force trace during the back foot contact phase.

Figure 2.9 – Typical force trace during the front foot contact phase.
Research into loading rates for pace bowlers is limited (Table 2.2). Hurrion et al. (1997b, 2000) defined and calculated the following parameters to allow loading rates to be compared:

- **Peak impact loading rate (PILR)** - divide the peak impact vertical force by the time of occurrence of the first impact peak after touchdown.

- **Peak vertical loading rate (PVLR)** - divide the maximum force during foot contact by the time of occurrence relative to initial touchdown.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Subjects</th>
<th>Mean Approach Speed (ms⁻¹)</th>
<th>PILR</th>
<th>PVLR</th>
<th>PILR</th>
<th>PVLRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurrion et al. (1997b)</td>
<td>6 fast-medium (outdoors)</td>
<td>4.84 ± 0.24</td>
<td></td>
<td></td>
<td></td>
<td>277 ± 39</td>
</tr>
<tr>
<td>Hurrion et al. (2000)</td>
<td>6 fast-medium (outdoors)</td>
<td>5.67 ± 0.27</td>
<td>79 ± 4</td>
<td>51 ± 9</td>
<td>298 ± 25</td>
<td>249 ± 64</td>
</tr>
</tbody>
</table>

Table 2.2 – Peak impact loading rates (PILR) and peak vertical loading rates (PVLR).

Hurrion et al. (2000) observed that PILR was higher than PVLR during both the back foot contact and front foot contact phases. Mean peak impact occurred 24 ms after touchdown for back foot contact and 16 ms after touchdown during front foot contact. Munro et al. (1987; as cited by Hurrion et al., 2000) reported a loading rate of 113 BW.s⁻¹ for middle distance runners at a speed of 5.0 m.s⁻¹, indicating the relatively high loading rates occurring during the front foot contact phase of the bowling action (in excess of 249 BW.s⁻¹). Hurrion et al. (2000) suggested these high loading rates may be associated with the use of footwear with little shock absorbency and elements of performance technique – such as a fully extended knee at front foot strike. Hurrion et al. (2000) also noted some bowlers demonstrated continuous ground contact during the delivery stride (i.e. at some stage both feet were on the ground) whilst others had discrete back and front foot contacts; no relationships were observed with the ground reaction forces recorded.

Elliott and Foster (1984) found approach speed at back foot contact to be higher for front-on bowlers (≈ 4.5 m.s⁻¹) than side-on bowlers (≈ 4.0 m.s⁻¹). However, no differences were observed between the two action classifications in terms of peak ground reaction forces during the front foot contact phase. This questioned the common viewpoint of coaches and journalists at the time who believed an inability to achieve a side-on orientation during the
delivery stride was the main cause of back injuries in fast bowlers. Furthermore, almost all bowlers attain a side-on position just prior to front foot contact regardless of whether they are front-on, mid-way or side-on at back foot contact. Portus et al. (2004) observed their stress fracture group displayed a series of non-significant trends in their ground reaction forces – higher peak vertical forces at back foot contact and a faster rate of peak vertical and braking force development during the front foot contact phase.

Portus et al. (2004) found knee angle at ball release showed a significant moderate positive correlation with both vertical and braking peak forces (Figure 2.10). Those bowlers with a straighter front knee at ball release experienced larger vertical and braking peak forces. Extension of the front knee between front foot flat and ball release was also linked to increased peak braking forces. The use of an extended / extending front knee was not only linked to increased peak ground reaction forces, these forces were also developed more rapidly. Significant moderate correlations were observed between the knee extension range during this phase of the bowling action and the time to peak vertical and braking forces ($r = -0.41$, $p < 0.01$ and $r = -0.41$, $P < 0.01$, respectively).

Figure 2.10 – The motion of the front knee during the front foot contact phase.

The use of a technique in which the front knee flexes during the front foot contact phase was recommended by Foster et al. (1989), in order to dissipate ground reaction forces and reduce the likelihood of injury. This claim was supported in unpublished work by Hall (1999) in a study of eight English club fast and medium pace bowlers. Bowlers who landed with a flexed front knee experienced lower ground reaction forces at front foot impact than those who landed with a straighter front knee (as cited by Elliott, 2000).

On the contrary, faster ball release speeds have been widely observed to be related to a higher release position (i.e. a more extended front knee at the instant of ball release)
(Burden and Bartlett, 1990a, 1990b; Davis and Blanksby, 1976b, as cited by Bartlett et al., 1996). The most convincing support for the role of the front leg in the generation of ball release speed was the large correlation observed by Portus et al. (2004) between time to peak vertical force and ball release speed. Bowlers with higher braking forces and developing their peak vertical and braking ground reaction forces more rapidly during the front foot contact phase released the ball at higher speeds. However, Stockill (1994; as cited by Bartlett et al., 1996) questioned these findings as he found no difference between two groups of twelve international standard junior and senior fast bowlers in terms of knee angle at ball release.

It has been proposed the ideal front leg technique is one in which the knee flexes initially to help attenuate impact forces, and then extends before ball release to enable increased ball release speeds (Bartlett et al., 1996). The extension component of this front leg technique (flexor-extender) may also enhance the work output contribution from the quadriceps musculature through stretch-shortening mechanisms (Walshe et al., 1998, as cited by Portus et al., 2004), as well as increase the height of ball release for extra bounce.

2.4 FAST BOWLING TECHNIQUE AND BALL RELEASE SPEED

Ball release speed is a major contributor to fast bowling success (Bartlett et al., 1996), reducing the time the batsman has to interpret the path of the ball and make decisions regarding which shot to play. Ball release speed is a common focus of fast bowling coaches. A number of researchers have previously investigated links between fast bowling technique and ball release speed. The findings of these studies will be summarised below; aspects of technique will be considered chronologically, according to the point in the action at which they occur.

2.4.1 RUN-UP SPEED

The effects of a variety of aspects of fast bowling technique on ball release speed have been investigated over the years, these include the length of run-up used by bowlers. Run-up length varies from bowler to bowler and there is currently no universal consensus as to its optimal length (Bartlett et al., 1996). Davis and Blanksby (1976a), in a study of 19 club
level fast bowlers, concluded that a 14 pace run-up was sufficient to release the ball at 37 m.s\(^{-1}\). The same investigators reported a 2.14 m longer run-up used by their 6 fastest bowlers in comparison with their 6 slowest bowlers, in a similar study of 17 fast bowlers (Davis and Blanksby, 1976b). No explanation was offered regarding the link observed between run-up length and run-up speed. Elliott and Foster (1989), on the other hand, suggested bowlers use a run-up length of between 15 and 30 m, with an emphasis on the use of a balanced and rhythmical running technique.

The effect of run-up speed on ball release speed has been the focus of many previous investigations. Elliott and Foster (1989) suggested run-up speed should be sufficient to produce as high a linear velocity of the body as possible for fast ball release speeds, whilst enabling the correct delivery technique to be adopted. It has been suggested that bowlers who use a front-on technique are able to run-up faster and contribute more of their horizontal velocity to the ball release speed than side-on bowlers, who have to change orientation during the pre-delivery stride (Elliott and Foster, 1984; Bartlett, 1992). Elliott and Foster (1984) reported run-up speeds, immediately before back foot strike, of \(3.9 \pm 0.1\) m.s\(^{-1}\) for two side-on bowlers in comparison to \(4.5 \pm 0.1\) m.s\(^{-1}\) for three front-on bowlers. These bowlers were from a group of Australian representative fast bowlers.

Davis and Blanksby (1976a) and Elliott \textit{et al.} (1986) attempted to calculate the percentage contribution of run-up speed to ball release speed. They subtracted the speed of the centre of mass, at ball release, from the ball release speed and reported values of 19\% and 15\%, respectively. However, Bartlett \textit{et al.} (1996) suggested these studies were flawed as they assumed all bowlers used the same bowling technique, instead the percentage contribution should vary from bowler to bowler.

Brees (1989) investigated the effects of experimentally manipulating run-up speed on ball release speed, kinematics of the delivery stride and accuracy. Bowlers were instructed to bowl as quickly and accurately as possible whilst using three different approach speeds – slow, normal, and fast. Run-up speed was positively correlated with ball release speed (\(P < 0.05\)) and negatively correlated with accuracy (\(P < 0.05\)), suggesting bowlers naturally choose an approach speed which is optimal for both speed and accuracy. Interestingly, increased run-up speeds were also associated with decreased flexion and lateral flexion of the trunk as well as increased front knee flexion between front foot strike and ball release. It should, however, be borne in mind that the “slow” and “fast” speeds were considerably
different to the run-up speeds used in matches. Hence these results may not hold true within the variability of run-up speeds present in match scenarios. Similarly, Glazier et al. (2000) observed a strong correlation between the horizontal velocity of the run-up, during the pre-delivery stride ($5.9 \pm 0.7 \text{ m.s}^{-1}$), and ball release speed ($r = 0.728, P < 0.05$). Burden (1990), on the other hand, in a two-dimensional cinematographic study of 10 college bowlers, fitted low order polynomials and observed no relationship ($r^2 = 0.01$) between the speed of the bowler at ball release and the ball release speed. It should be noted, however, that Burden (1990) measured run-up speed at the instant of ball release and therefore the measured value is unlikely to be representative of the actual run-up speed.

2.4.2 DELIVERY STRIDE

Previous research has also addressed the relationships between ball speed and bowling technique during the delivery stride. The MCC (1976) state that a bowler’s weight should be on their back foot at back foot contact, leaning away from the batsman. This is similar to some javelin throwing techniques and may serve the purpose of increasing the acceleration path of the ball, as suggested by Bartlett and Best (1988). Links between delivery stride length and ball speed have not been reported; although the length of the delivery stride has been linked to run-up speed and the physique of the bowler (MCC, 1976; Elliott et al., 1986). Elliott and Foster (1989) noted that the bowler with the slowest approach speed in their study ($3.8 \text{ m.s}^{-1}$) had the shortest delivery stride (1.34 m), whereas the bowler who ran in quickest (4.6 m.s$^{-1}$) had the longest delivery stride (1.67 m). However, in a subsequent investigation (Elliott and Foster, 1989) they warned that bowlers approaching the crease with excessive speed will often have a reduced delivery stride; this “uncontrolled” approach may inhibit the ability to master a side-on delivery. There is currently insufficient evidence to substantiate a general conclusion on the relationship between stride length and run-up speed (Bartlett et al., 1996).

2.4.3 FRONT KNEE TECHNIQUE

A number of studies have reported relationships between the motion of the front knee during the front foot contact phase of the fast bowling action and ball release speed. Portus et al. (2004) noted a trend for bowlers who extended their front knee to bowl faster than
those who flexed or extended their knee less (front foot contact phase knee extension, $r = 0.37$, $P = 0.02$). Similarly, Burden and Bartlett (1990b) reported a significant correlation between ball release speed and knee angle at ball release ($r = 0.41$). Furthermore, bowlers who did not flex their front knee after front foot strike released the ball significantly faster than those who did ($P < 0.02$). It has been suggested a front knee that extends, or is extended, during the front foot contact phase may permit a more efficient transfer of kinetic energy to the ball and facilitate faster ball release speeds (Elliott et al., 1986; Portus et al., 2004). Elliott et al. (1986) suggested a knee angle greater than 150° would be sufficient to provide this benefit.

Burden and Bartlett (1990a) reported the greatest difference between their two groups of bowlers, one containing elite fast bowlers and the other consisting of college medium-fast bowlers, was the behaviour of the front knee between front foot contact and ball release. Portus et al. (2004) grouped bowlers according to their front knee classification (flexor, flexor-extender, extender or constant brace) and compared ball release speeds between groups. Although there were no significant differences, ball speeds were generally faster for extenders and flexor-extenders. In contrast, Stockill (1994) found no such difference between two groups of 12 international senior and junior fast bowlers.

There is no conclusive agreement at present regarding the importance of the front knee in determining ball release speed (Bartlett et al., 1996). It has been proposed that the ideal front leg technique is one in which the knee flexes at front foot strike, to help attenuate impact forces, then extends before ball release to enable increased release speeds (Bartlett et al., 1996). Such a technique (“flexor-extender”) is rare; Burden (1990) identified 2 of 9 bowlers and Stockill and Bartlett (1992a) found 2 of 17 bowlers who flexed on impact and subsequently extended by more than 15°. Similarly, Portus et al. (2004) observed that just 4 of 42 bowlers were flexor-extenders using a lower threshold of 10°. These techniques are, however, more common in javelin (Komi and Mero, 1985). It should be emphasised that the role of the front knee in the attenuation of impact forces has not been substantiated (Bartlett et al., 1996) and will be investigated further within Chapter 7 of this thesis.
2.4.4 THORACIC MOTION

Stockill and Bartlett (1992b) investigated relationships between ball release speed and parameters typically used to classify bowling actions, namely the orientations of the pelvis and shoulders at back foot contact, as well as the degree of shoulder counter-rotation during the delivery stride. No significant relationships were found, suggesting action type (front-on, side-on, or mixed) was not, in itself, a valid predictor of ball release speed. While further investigation is required into this area, results suggest there is no reason, in terms of performance maximisation, why the mixed action should be adopted, especially considering the reported injury risks (Foster et al., 1989; Elliott et al., 1992, 1993).

Portus et al. (2004) observed a significant relationship between ball release speed and the timing of the maximum pelvis-shoulder separation angle during the delivery stride. Bowlers who achieved a maximum separation angle after the instant of front foot strike bowled faster than those whose maximum occurred before front foot strike \( (r = 0.34, P = 0.05) \). The range of shoulder girdle rotation (shoulder forwards rotation) preceding ball release was also correlated with ball release speed \( (r = 0.30, P = 0.05) \). Shoulder forwards rotation appeared to be significantly more important in producing faster ball release speeds than shoulder counter-rotation which had no correlation with ball release speed \( (r = 0.009, P = 0.95) \). These findings would appear to be true anecdotally within the coaching domain, where it is often suggested that higher ball release speeds are obtained when technique is smooth and rhythmical as opposed to an extreme effort to bowl fast. It has also been suggested these “well timed” rotations of the segments of the trunk also reduce the stress in the lumbar region (Foster et al., 1989; Portus et al., 2004).

Trunk flexion has been reported to provide a significant contribution to the speed of the ball at release. Davis and Blanksby (1976b) and Elliott et al. (1986) calculated that trunk flexion contributed to 11% and 13% of the final ball release speed, respectively. Burden and Bartlett (1990a) compared trunk flexion-extension angles between a group of nine college bowlers and a group of seven county and international bowlers. Trunk angles were similar for both groups at back foot contact and front foot contact, with the difference occurring between front foot contact and ball release. The county and international bowlers exhibited higher maximum trunk angular velocities \( (529°.s^{-1}) \) than the college bowlers \( (355°.s^{-1}) \) and were in a more flexed position at ball release \( (49° \) in comparison to \( 60°) \) (Figure 2.11).
2.4.5 BOWLING ARM

Relatively few studies have considered the effect of the motion of the bowling arm during the delivery stride on ball release speed. Tyson (1976) suggested the arm position at the instant of front foot strike is a good predictor of ball release speed, with faster bowlers delaying the onset of upper arm circumduction for as long as possible. However, no subsequent research has been identified as supporting this (Bartlett et al., 1996). Davis and Blanksby (1976b) considered the position of the arm at the instant of ball release; quicker bowlers released the ball with the arm in front of the line of the trunk (mean 158°). This finding has been supported in a number of more recent studies (Elliott et al., 1986; Burden and Bartlett, 1989; Foster et al., 1989; Burden, 1990). Foster et al. (1989) reported a high ball release point in relation to the bowler’s standing height was significantly correlated with the occurrence of stress fractures in the lower back, but little has been reported regarding its effect upon ball release speed. The height of ball release relative to standing height has ranged from 114% (Elliott et al., 1992) to 116% (Elliott and Foster, 1984) and as high as 118% (Foster and Elliott, 1985). Ball release height is likely to be related to the length of the delivery stride, the knee angle at ball release, and the amount of trunk flexion and lateral flexion at ball release. Currently, no results have been reported as to the relationships between these variables. Similarly, only limited research has been conducted into the relationship between elbow extension and ball release speeds. Portus et al. (2006), when using an arbitrary threshold of 15° of elbow
extension, found ball speeds for deliveries above this threshold (39.5 ± 2.0 m.s\(^{-1}\)) were significantly faster (effect size = 1.4; \(p = 0.006\)) than deliveries below the threshold (37.1 ± 1.4 m.s\(^{-1}\)).

2.5 CHAPTER SUMMARY

Previous research into fast bowling has focused predominantly on links between fast bowling action classification and the occurrence of lower back injuries. The more recent studies have suggested the orientation of the lower back during the early part of the front foot contact phase of the delivery stride, when peak ground reaction forces occur, may be the cause of the high prevalence of lower back injuries observed in fast bowlers. Peak ground reaction forces and loading rates have been reported, however, no consensus has been reached regarding their interactions with the motion of the front leg during the front foot contact phase. Similarly, although a number of studies have looked to identify technique variables linked to ball release speed, none have considered the interaction between aspects of technique. This study will use three dimensional kinematic data in conjunction with kinetic data to investigate the mechanics of generating ball speed and the effect of the motion of the front leg on ground reaction forces and the forces transmitted to the lower back.
3.1 EQUIPMENT

Data were collected over three separate data collection sessions (September 2007, 2008 and 2009) at the England and Wales Cricket Board (ECB) National Cricket Performance Centre, Loughborough University. The equipment, layout and procedures used were the same in all data collection sessions. The indoor practice facility allowed subjects to bowl using their normal run-up on a standard sized, artificial cricket pitch. A Kistler force plate (Type 9287B – 900 x 600 mm), with a 25 mm covering of artificial grass on its surface, was permanently installed in the facility and located at the bowling crease.

![Figure 3.1 – The data collection environment.](image-url)
A Vicon Motion Analysis System (OMG Plc, Oxford UK) was used to collect synchronous kinematic and kinetic data. Eighteen cameras (M² MCam), operating at a frequency of 300 Hz, were positioned to cover a volume of approximately 7 x 3 x 3 m (Figure 3.1). Black fabric was draped along the walls of the bowling facility to reduce glare from the sun; any source of infrared light is seen by the cameras and reduces the accuracy of the data collected. The Vicon Motion Analysis System’s accuracy is also reduced when cameras can see each other in their field of view. To avoid this, sixteen of the Vicon cameras were mounted on tripods with 1 m extension poles attached, allowing the cameras to be pointed downwards slightly. The two remaining cameras were positioned at a lower height and located at the front of the volume. These cameras were used to reduce the occlusion of markers on the front of the bowlers’ pelvis and thorax as they flexed forwards during the delivery action.

The Vicon system was calibrated at the start of each day of data collection using an Ergocal (14 mm markers) static calibration frame, to define the origin and global coordinate system, and a 240 mm calibration wand (14 mm markers). When viewed from behind, the global origin was located at the back-left corner of the force plate; the x-axis pointed from left to right, the y-axis pointed forwards and the z-axis was the upwards vertical.

Two Phantom v4.1 digital high-speed cameras were used to capture all bowling deliveries; this footage was not used directly in this thesis, but provided a useful source of reference. Both cameras recorded at a frequency of 500 Hz and were positioned behind the bowler (Figure 3.2A) and to the side (Figure 3.2B). A 50 Hz camera (shutter speed of 1/1000 s) was connected to the Vicon system, providing a visual prompt when viewing or analysing the data within Vicon. Force data for all bowling trials were recorded as an analogue signal within Vicon (1200 Hz) and also using Kistler’s Bioware v.3.22 software (1008 Hz).
3.2 PARTICIPANTS

Thirty elite fast bowlers were tested over the course of the three data collection sessions. All bowlers were identified as “fast bowlers” by ECB fast bowling coaches. Each bowler was either a member of the England men’s senior or U19 cricket team, or a current professional first class county player identified by the ECB fast bowling coach as having the potential to play for England within the next 5 years. Two of these subjects withdrew from the investigation during the data collection session as they were unable to bowl at maximum pace without discomfort from recent injuries. A further eight bowlers were eliminated from the study as they did not perform a sufficient number of deliveries in which the force plate was hit cleanly during front foot contact with crucial markers remaining affixed to their body. The remaining twenty bowlers formed the basis of this investigation (mean ± standard deviation: age 20.1 ± 2.6 years; height 1.88 ± 0.08 m; body mass 81.5 ± 7.1 kg). See Appendix 1 for details of individuals’ data.

All subjects were deemed fit to bowl by their County Physiotherapist and had bowled a minimum of three times per week, on average, in either practice sessions or matches during the current season. Subjects were selected in an attempt to ensure that a range of bowling actions (i.e. side-on, front-on, mid-way and mixed) and front-leg techniques (i.e. flexor, extender, flexor-extender and constant brace) were represented. The testing procedures were explained to each subject in accordance with Loughborough University ethical
guidelines and an informed consent form was signed (Appendix 2). All subjects conducted a thorough warm-up prior to commencing data collection.

### 3.3 MARKERS

Forty-seven 14 mm retro-reflective markers were attached to each subject using a sports adhesive spray and double-sided tape. Markers were positioned over bony landmarks in accordance with a marker set developed specifically for this project (Figure 3.3). Details of the marker positions are provided in Appendix 3.

![Figure 3.3](image)

**Figure 3.3** – An illustration of the positions of the forty-seven markers used.

An additional marker, in the form of a 15 x 15 mm patch of 3M Scotch-Lite reflective tape was attached to the ball (Figure 3.4), enabling ball speed and the instant of ball release to be determined.

![Figure 3.4](image)

**Figure 3.4** – Illustration of the ball marker.
3.4 TESTING PROTOCOL

Data collection commenced with the acquisition of a static trial; the subject stood in an anatomical position with their arms by their side and their wrists straight (Figure 3.5A). This trial enabled the length of body segments to be determined and joint offset angles to be calculated (see Chapter 4).

(A) 

(B)

Figure 3.5 – Illustration of the initial trials recorded: (A) Static (with marker positions illustrated) and (B) Range of motion (with the lines of the pelvis and lower back illustrated).

A range of motion trial was performed (Figure 3.5B), following the protocol of Ranson et al. (2008) to determine the range of motion of a lower back reference frame relative to the pelvis reference frame. Bowlers were given a demonstration on how to move to their end range of active lower trunk flexion and extension, side-flexion to both sides, and left and right axial rotation. Participants were instructed to keep their legs straight throughout the trial and to maintain a static pelvis position while side-flexing and rotating their trunk. Hence, the proportion of available lower back range of motion used during the bowling action could be determined. A neutral position of the spine was obtained from the range of
motion trial. This was defined to be the moment the spine passed through the vertical as the bowler went from side-flexion one way to side-flexion in the other direction. This enabled orientation angles of the lower back relative to the pelvis to be normalised (see Chapter 4). Subjects then performed six maximum velocity bowling trials, deemed to be of good length by the ECB head fast bowling coach, striking the force plate with their front foot during the front foot contact phase of the bowling action.

3.5 ANTHROPOMETRIC DATA

Segmental inertia parameters for each subject were required as an input to the models developed, these were determined using Yeadon’s geometric model (1990). This model has been used successfully in previous studies (e.g. Wilson, 2003; Glynn, 2007), enabling subject-specific inertia parameters to be determined for subjects with little inconvenience caused to them. Ninety-five anthropometric measurements were taken at specific points on the body by an experienced researcher, these included: lengths; widths; depths; and perimeters. This enabled the body to be split into the required 18 segments. Yeadon’s model used the segmental density values of Chandler et al. (1975) as initial estimates and subsequently varied these values within a subroutine until there was a match between the whole body mass determined by the model and the subject’s body mass as measured using Seca Alpha digital scales.

3.6 DATA PROCESSING

Prior to developing a model and analysing the techniques used by the bowlers, kinematic data were filled (where necessary) and filtered; the key instants in the bowling action were also identified. Although every effort was made to maximise the accuracy of the data, due to the dynamic nature of the fast bowling action, it was inevitable that some small gaps would be present in the marker trajectories during the delivery action. Similarly, there was some noise within the data, this could be due to either markers wobbling on the skin, or due to the inability to track all markers accurately throughout the entire action. The best three trials – maximum pace deliveries with minimal marker loss – were identified for each bowler for inclusion in this study.
3.6.1 IDENTIFICATION OF CRUCIAL INSTANTS

In order to compare and process trials appropriately, it was necessary to identify the frames corresponding to: the instant of back foot contact and ball release. Back foot contact was identified using the three-dimensional trajectories of the markers on the foot. The instant of ground contact was identified as the first frame in which the motion of the foot was seen to change due to contact with the ground. The instant of ball release was identified by calculating the distance between the wrist joint centre and the marker on the ball. The ball was defined to have left the hand once the change in the distance between consecutive frames exceeded 20 mm (Figure 3.6).

![Figure 3.6](image)

**Figure 3.6** – A graph of the change in distance between the marker on the ball and the mid-point of the markers on the wrist. The identified instant of ball release is indicated by the arrow.
3.6.2 GAP FILLING

Very few gaps were present during the specific period of interest in the bowling action (from back foot contact until ball release). The maximum duration of gaps in this period was 8 frames (0.023 s). These gaps were filled using the “spline fill” function within Vicon’s BodyBuilder software; a spline is fitted to the data either side of the gap and interpolated to estimate the missing values (Figure 3.7). On each occasion filling was performed, the new data was visually inspected to ensure the filled values were sensible. Illustrations of the filling performed using the three different methods used in this study are provided in Figures 3.7, 3.8 and 3.9.

![Figure 3.7](image)

**Figure 3.7** – Example of the filling of a small gap in a trajectory using “spline fill”. The filled data is represented by the dashed line.

Typically, gaps were more common and longer in duration at the start and end of the trial (prior to back foot contact and after ball release). Although these sections of the delivery action were not directly of interest within this study, the period of 18 frames prior to back foot contact was used to estimate the run-up speed. When possible, gaps with a duration of more than 10 frames were filled using a dummy reference frame. However, this can only be used when there are four or more markers with fixed locations relative to each other. Consequently this method was only applied to the pelvis and head markers. If one of these markers had a gap in its trajectory, a dummy coordinate system was defined using the other three fixed markers. A mean position for the marker with gaps in its trajectory was
calculated over the entire trial in the dummy reference frame. This was used to estimate the marker’s position in frames in which it was not visible (Figure 3.8).

**Figure 3.8** – Illustration of a gap filled using a dummy reference frame. The filled data is represented by the dashed line.

As stated previously, a dummy reference frame can only be used to fill gaps when there are four markers with fixed locations relative to each other. In other situations, the “copy trajectory” function in Vicon’s BodyBuilder software was used. This enabled gaps to be filled using the trajectory of a second marker which moved in a similar way (Figure 3.9)

**Figure 3.9** – Illustration of a gap filled using the “copy trajectory” function.
3.6.3 FILTERING

All marker trajectories were filtered prior to being used in the model. Although these trajectories were relatively smooth, noise was magnified when differentiated in order to calculate velocities and accelerations. All kinematic data were filtered using a fourth order Butterworth filter (double-pass) with a low pass cut-off frequency. Cut-off frequencies were evaluated using a residual analysis, in addition to the peak difference between the raw and filtered data. The determination of the cut-off frequency (fc’) to use was a compromise between the amount of signal distortion and the amount of noise allowed through; the method suggested by Winter (1990) was used, assuming both errors should be equal (Figure 3.10). A cut-off frequency of 30 Hz was chosen to be applied to all marker positions, this reduced the noise in the velocities and accelerations but made little difference to the position of the markers (Appendix 4).

![Figure 3.10](image)

**Figure 3.10** – Illustration of the method used to identify an appropriate cut-off frequency (fc’) (Winter, 1990).
3.7 CHAPTER SUMMARY

This chapter has provided details of the testing procedures used in the three data collection sessions and details of the participants involved in this study. Marker positions were described and the data processing required prior to trials being analysed. The methods used to fill gaps in the marker trajectories has been illustrated and the level of filtering applied justified.
This chapter provides details of the inverse dynamics analysis performed on the data collected during this study. The segmentation of the body and the location of joint centres will be described for an eighteen segment representation of the human body developed to analyse the fast bowling action. The inverse dynamics analysis enabled joint angles, centre-of-mass locations, and internal forces and moments to be calculated for the bowlers. The calculation of the parameters used in subsequent chapters are explained in addition to the statistical tests performed.

### 4.1 18 SEGMENT REPRESENTATION OF A BOWLER

A whole-body inverse dynamics analysis was performed using BodyLanguage, within Vicon’s BodyBuilder software (Appendix 6). The human body was represented as a system of 18 rigid segments: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two-segment foot (Figure 4.1). A three-dimensional local coordinate system was defined for each segment, using three markers located on the segment itself, allowing segment orientations and joint angles to be calculated.

![Figure 4.1](image.png) – Illustration of the 18 segment representation of the human body.
4.2 SEGMENTATION OF THE BACK

During the fast bowling action, the spine undergoes a number of complex motions. Although the constituent parts of the spine have 6 degrees-of-freedom; the discs are able to deform, allowing the vertebrae to rotate and translate; the spine as a whole is only able to produce flexion-extension, lateral flexion and axial rotation (Zatsiorsky, 1998). The spine’s flexibility varies along its length (Figure 4.2). The thoracic spine can only produce limited amounts of flexion-extension and lateral bending, due to its thin intervertebral disks, the configuration of the articular facets, and the apposition of the spinous processes. The thicker intervertebral discs in the lumbar region of the spine allow large amounts of flexibility in flexion-extension and lateral bending, but axial rotation is restricted due to the articular facets. The cervical region exhibits three degrees-of-freedom due to the occipital-atlanto-axial complex which has two rotational degrees-of-freedom and the atlas which can move independently (Zatsiorsky, 1998).

![Figure 4.2](http://www.drhope.net/images/spineview.jpg)

In the current study, in order to calculate meaningful parameters describing the motion and loading acting in the lower back of fast bowlers, it is essential that the back is represented in sufficient detail. Roosen (2007) conducted range of motion trials comprising flexion-extension, lateral bending and axial rotation of the spine. Since no distinguishable
movement was found to occur between the head and cervical spine, he concluded the head and cervical spine could be modelled as a single segment. It was therefore decided that a 3 segment back would be used in the current study: lower back; upper back; head and neck. These segments will be defined later in this chapter.

4.3 JOINT CENTRE LOCATIONS

A pair of markers were positioned across each joint, such that their mid-point coincided with the joint centre. The only exceptions were the hips and the segments of the back and head. Marker pairs were positioned to ensure their mid-point coincided with the joint centre when the segment was in a typical orientation during the bowling action, e.g. markers defining the shoulder joint centres were positioned with the upper arm overhead (Appendix 3). The methods used to locate the hip joint centres and those of the back are described below.

4.3.1 HIP JOINT CENTRES

The hip joint centres (RHJC and LHJC) were calculated using the algorithm of Davis et al. (1991), based on the radiographic examination of 25 hip studies. The coordinates of RHJC and LHJC, relative to a local pelvis coordinate system (defined in Section 4.4.1), were:

\[
X_{coordinate} = S \left[ C \sin(28.4) - \frac{d_{ASIS}}{2} \right]
\]

\[
Y_{coordinate} = \left[ -x_{dis} - r_{marker} \right] \cos(18) + C \cos(28.4) \sin(18)
\]

\[
Z_{coordinate} = \left[ -x_{dis} - r_{marker} \right] \sin(18) - C \cos(28.4) \cos(18)
\]

Where,

\[ S = +1 \text{ for the left side; and } -1 \text{ for the right side} \]

A leg length was calculated for each leg, during a static trial, as the distance from the hip joint centre to the lateral ankle marker, going via the lateral knee marker. The mean of these two values was defined as LegLength.
C (m) = 0.115*LegLength – 0.0153

d_{ASIS} (m) = distance between the bony protrusions on the left and right anterior superior iliac (LASI and RASI, respectively).

r (m) = marker radius.

x_{dis} (m) = anterior / posterior component of the ASIS / hip centre distance in the sagittal plane of the pelvis and measured during clinical examination. This was estimated, as in Vicon’s generic Golem model, using the formula:

\[ x_{dis} = 0.0001288 \times \text{LegLength} – 0.04856. \]

### 4.3.2 JOINT CENTRES OF THE BACK

Joint centres for the lower back (LOWJC), upper back (MIDJC) and the head and neck segment (TOPJC) were defined using the methodology of Roosen (2007). These joint centres were located using the positions of the anatomical markers located on the left and right superior iliac (LASI and RASI), the left and right posterior superior iliac (LPSI and RPSI), the proximal (sterna) and distal (clavicular) ends of the sternum (STRN and CLAV) and the spinous processes of T10 and C7 (T10 and C7). These three joint centres were defined as:

LOWJC = SACR + 0.2 \times (PELF – SACR)

where,

SACR = (RPSI + LPSI) / 2

PELF = (RASI + LASI) / 2

MIDJC = T10 + 0.125 \times (FThorax – BThorax)

where,

FThorax = (CLAV + STRN) / 2

BThorax = (C7 + T10) / 2

TOPJC = C7 + 0.125 \times (C7 – CLAV).
4.4 SEGMENT DEFINITIONS

Within BodyLanguage, each segment was represented by a right-handed coordinate system. These were positioned at the lower joint centre of the segment when standing in an anatomical position. Segments were defined such that when in an anatomical position, the z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed to the subject’s right (representing the flexion-extension axis of the joint) and the y-axis pointed forwards, representing the frontal axis (Figure 4.3). The longitudinal axis was typically defined to join the proximal and distal joint centres of the segment, exceptions to this are described below.

Figure 4.3 – Illustration of the orientation of the 18 segments’ coordinate axes (with and without an outline of the body drawn).

A local coordinate system was defined for each segment by specifying the origin, two defining lines and the order of axis specification:

\[ \text{e.g. } \text{Segment} = \{ \text{Origin, 1st Defining Line, 2nd Defining Line, Axis Order (e.g. zyx)} \} \]
In this case (with axes being specified in the order xyz),

\[ z\text{-axis} = 1^{st} \text{ Defining Line} \]

\[ y\text{-axis} = (2^{nd} \text{ Defining Line}) \times (1^{st} \text{ Defining Line}) \]

\[ x\text{-axis} = \text{the coordinate axis required to complete a right-handed coordinate system.} \]

In general, segments were defined using a zyx axis order, specifying the z-axis (longitudinal axis of the segment) directly. A vector joining the pair of markers at the joint (parallel to the sagittal axis of the segment) was used as the second defining line. This corresponds to the recommended format of segment definitions in BodyBuilder (Oxford Metrics Ltd., 2002). The exceptions when this methodology was not used are described below. These were the segment definitions for the: pelvis; lower-back; upper-back; head and neck; toes; and hands.

\subsection*{4.4.1 PELVIS SEGMENT}

Due to a lack of markers defining a “longitudinal” axis of the pelvis and the longest axis being the sagittal axis, an xzy axis order was used to define the pelvis segment. The vector joining LASI and RASI was used as the first defining line, and the second defining line joined PELF and SACR (Section 4.3.2). The origin was positioned at the midpoint of the hip joint centres (Section 4.3.1).

\subsection*{4.4.2 UPPER AND LOWER-BACK SEGMENTS}

Upper and lower-back segments were defined using a zxy axis sequence; markers on the thorax did not allow the specification of a sagittal axis. Two virtual markers were defined for use in axis definitions:

\[ \text{FThorax} = (\text{CLAV + STRN}) / 2 \]

\[ \text{BThorax} = (\text{C7 + T10}) / 2 \]

The lower-back segment axes were positioned at LOWJC (see Section 4.3.2) and were defined using vectors joining SACR and the spinous process of L1 (LUM1), and LUM1
and STRN, as the first and second defining lines, respectively. Similarly, the origin for the upper-back was located at MIDJC, and was defined using vectors joining LUM1 and C7, and BThorax and FThorax.

### 4.4.3 Head and Neck Segment

Four additional virtual markers were defined in order to specify the head and neck segment, these used the four markers on the head – right back head (LBHD), left back head (LBHD), right front head (RFHD) and left front head (LFHD):

\[
LHead = \frac{(LFHD + LBHD)}{2}
\]

\[
RHead = \frac{(RFHD + RBHD)}{2}
\]

\[
BHead = \frac{(LBHD + RBHD)}{2}
\]

\[
FHead = \frac{(LFHD + RFHD)}{2}
\]

Due to inaccuracies introduced by variations in the position of the head markers from subject to subject, a head reference frame was defined (HeadRef). An xyz axis sequence was used and the defining lines: \((RHead – LHead)\) and the global z-axis. HeadRef represented the head segment in the static trial using a coordinate system with its y-axis parallel to the ground. A temporary head and neck segment was also specified: \((RHead – LHead)\) and \((BHead – FHead)\) and an xzy axis sequence (equivalent to HeadRef once rotated about the x-axis). An offset between these two reference frames (HeadFlexOS) was calculated and stored for each subject; enabling a corrected head and neck segment to be defined in the dynamic trials.

### 4.4.4 Toe and Hand Segments

A foot reference frame (FootRef) was defined to rotate the toe segments, to account for the TOE marker being positioned on top of the foot (Appendix 3). Using a static trial, with both feet flat on the ground, a virtual marker was defined for each foot (LRF and RRF, for the left and right feet respectively) with the x- and y-coordinates of the ankle joint centre and the z-coordinate of the MTP joint centre. FootRef was a foot segment with a z-axis
parallel to the ground, defined using the virtual marker and the markers on the metatarsophalangeal (MTP) joint. The angle between FootRef and the toes segment was stored for each bowler (FootRefOS) and used to rotate the toe segment in bowling trials. In the same way, a correction was also applied to the hand segments using an offset calculated during the static trial in which subjects had their wrists straight.

4.5 ANGLE DEFINITIONS

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) to bring it into coincidence with the child segment (distal segment). The pelvis segment was defined to be the only segment without a parent; rotation of the femur and lower back were both defined with the pelvis as the parent segment. Rotation angles were calculated using an xyz sequence - representing an initial rotation about the x-axis of the parent, followed by rotation about a floating y-axis of the parent and finally the z-axis of the child. These rotations correspond to flexion-extension, abduction-adduction or valgus-varus rotation, and longitudinal rotation, respectively. Positive angle changes and zero angle positions were defined as detailed in Table 4.1.

Table 4.1 – Details of the joint angles calculated.

<table>
<thead>
<tr>
<th>Joint</th>
<th>+ve x</th>
<th>Anatomical Position (°)</th>
<th>+ve y</th>
<th>Anatomical Position (°)</th>
<th>+ve z</th>
<th>Anatomical Position (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow; Wrist; Knee; Ankle;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>Extension 180</td>
<td>Lateral motion</td>
<td>0</td>
<td>Supination</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Lumbar; Thoracic; Cervical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>Extension 180</td>
<td>Tilt right</td>
<td>0</td>
<td>Twist left</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>Flexion 0</td>
<td>Lateral motion</td>
<td>0</td>
<td>Supination</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Extension 180</td>
<td>Lateral motion</td>
<td>0</td>
<td>Supination</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.6 SEGMENTAL PROPERTIES

The mass, position of the centre of mass and the three principal moments of inertia of each segment were defined using the output from the geometric model of Yeadon (1990) for each bowler. The geometric model was customised to produce parameters for the eighteen segment representation developed for this study. It was assumed the levels of the body defined by the geometric model of Yeadon (1990) were equivalent to the positions detailed below:

**Table 4.2** – Details of the assumptions made regarding the correspondence of the levels of the geometric model of Yeadon (1990) and the joint centres defined in this study.

<table>
<thead>
<tr>
<th>Yeadon’s Level</th>
<th>Equivalent Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acromion</td>
<td>TOPJC</td>
</tr>
<tr>
<td>Lowest Front Rib</td>
<td>MIDJC</td>
</tr>
<tr>
<td>Umbillicus</td>
<td>LOWJC</td>
</tr>
<tr>
<td>Ball</td>
<td>MTP</td>
</tr>
</tbody>
</table>

To ease the implementation of segmental parameters determined using the geometric model of Yeadon (1990), additional segment coordinate systems were defined for each segment within the BodyLanguage code. These were identical to the segmental coordinate systems previously described, but with the origin relocated to the proximal joint of the segment. It was assumed the longitudinal axes of the segments (z-axis) defined within the BodyLanguage code corresponded exactly to those of Yeadon (1990). The longitudinal axis (z-axis) of each segment in the 18 segment system corresponded to the longitudinal axis in Yeadon’s model.

This enabled the calculation of the motion of the whole body centre of mass for each bowler and the subsequent calculation of the internal forces and moments at each joint during the bowling action. It was assumed that the centre of mass of the head and neck was located vertically above the joint centre (TOPJC) in the static trial. The adjusted segment axes enabled the position of the segment’s centre of mass to be calculated in the dynamic trials. The segmental properties of the bowling hand were adjusted to account for the ball. An additional mass of 159 g was placed midway between the level of the knuckles and finger nails in the Yeadon’s model (1990) on the longitudinal axis of the
hand. The three principal moments of inertia were also adjusted, assuming the ball was uniform and had a radius of 36 mm.

4.7 INVERSE DYNAMICS

To perform inverse dynamics calculations using BodyLanguage, a kinetic hierarchy must first be defined. This requires the specification of: segment name; parent segment; connection point between the two segments; and segmental parameters (mass, centre of mass position, and the three principal moments of inertia). Connection points were defined as the joint centres; the body was represented as a system of rigid segments connected by pin joints. The kinetic hierarchy was defined with the head and neck as the “root” segment as illustrated in Figure 4.4. Calculations were performed starting from the foot on the force plate, working upwards towards the “root” segment.

Figure 4.4 – The kinetic hierarchy used in the inverse dynamics calculations.
Force data collected using the Vicon system was automatically integrated with the kinematic data. Internal tests identify the segment to which the ground reaction forces should be applied. These tests consider: the magnitude of the ground reaction force; the position of the segment’s origin and its attachment point; and the velocity of the closest end of the segment to the plate. All trials were checked manually to ensure the ground reaction force had been connected to the correct segment. The forces and moments acting at a particular joint are calculated using the “reaction” function in BodyLanguage. This routine calculated the internal joint forces and moments acting on the child segment at a joint; forces and moments were expressed in the local coordinate system of the child segment at all joints. Positive forces acted in the direction of the coordinate axes and positive moments acted in an anti-clockwise direction about the coordinate axes (Figure 4.5).

![Diagram showing direction of positive forces and moments.](image)

**Figure 4.5** - Diagram showing direction of positive forces and moments.

The moments calculated at the ankle, knee and hip using the inverse dynamics analysis were compared with those obtained using quasi-statics for a static balance on one leg (Table 4.3). This enabled the validation of the calculated joint moments from the inverse dynamics analysis.
Table 4.3 – Comparison of the moments calculated at the ankle, knee and hip for a static balance using inverse dynamics and quasi-statics.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Inverse Dynamics</th>
<th>Quasi-Statics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mx (N.mm)</td>
<td>My (N.mm)</td>
</tr>
<tr>
<td>Ankle</td>
<td>-69686</td>
<td>-10241</td>
</tr>
<tr>
<td>Knee</td>
<td>-11983</td>
<td>35708</td>
</tr>
<tr>
<td>Hip</td>
<td>-46607</td>
<td>50024</td>
</tr>
</tbody>
</table>

There was good agreement between the two methods in terms of the flexion-extension moment (Mx) at the ankle and knee. There was a larger discrepancy between the two measures at the hip, however, a quasi-static approach is less accurate higher up the leg. There was reasonable agreement at the knee in terms of both My and Mz. The large difference between the two methods at the ankle in My and Mz is because the y and z-axes in the global reference frame and the local reference frame of the foot are not coincident. If the resultant moment about the y and z-axes is calculated for both methods at the ankle, these are again very similar – 12899 N.mm using inverse dynamics and 12346 N.mm for quasi-statics. This confirmed the inverse dynamics calculations performed were sensible and could be used to provide a reasonable estimation of the internal forces and moments acting at the joints of the 18 segment representation of the human body.

4.8 DATA REDUCTION

The calculation of the parameters describing aspects of bowling technique are explained in the following section. The parameters are defined in groups, according to the particular aspects of technique they correspond to.

4.8.1 RUN-UP SPEED AND BALL RELEASE SPEED

The horizontal run-up speed (in the global y-direction) was calculated during a period of 18 frames, ending one frame prior to the instant of back foot contact. It was assumed the bowler’s centre of mass had a constant linear velocity during this period. The ball release
speed was calculated in a similar manner, using the motion of the marker on the ball. Ball release speed was calculated over a period of 10 frames, starting from the instant of ball release. The ball was assumed to move with a constant velocity in the global x and y-directions. The vertical velocity of the ball (global z-direction) was calculated by using a constant acceleration equation during this period \( s = u.t + \frac{1}{2}.a.t^2 \). The speed of ball release was defined as the magnitude of the velocity at the instant of release.

### 4.8.2 FRONT LEG MOTION

The flexion-extension angle of the ankle, knee and hip were calculated at the instants of: front foot contact; front foot flat; and ball release. These corresponded to the value of the \( x \)-component of the joint angle calculated in the inverse dynamics analysis. Front foot contact and front foot flat were identified using the motion of the markers on the front foot. Front foot contact was the first frame in which the motion of the markers was observed to change due to contact with the ground – the frame identified was verified using the ground reaction force data collected. The instant of front foot flat was the first frame in which the forefoot was observed to touch the ground. The instant of ball release was identified using the markers placed on the wrist of the bowling arm and also the marker on the ball (as detailed in Section 3.6.1). The amount of knee flexion and extension occurring between front foot flat and ball release were calculated using the angle-time history of the \( x \)-component of the knee angle.

Additional parameters were calculated describing: plant angle; manner of foot-strike; and stride length. The plant angle was calculated by projecting the position of the hip and ankle joint centres, at the instant of front foot contact, onto a global y-z plane (Figure 4.6A). The plant angle corresponded to the angle between a line joining the projected joint centres and the downwards vertical. Similarly, the manner of foot-strike was calculated by projecting the joint centres of the ankle and MTP joint onto the same global y-z plane (Figure 4.6B). The measured value for the foot-strike indicator was the angle between the line joining the projected joint centres and the global horizontal. Stride length was defined as the distance between the ankle joint centre of each leg, in the global x-y plane, at the instant of front foot contact (Figure 4.6C). To enable stride length to be compared between bowlers, it was expressed as a percentage of the bowler’s standing height.
Figure 4.6 – An illustration of the calculation of the: (A) plant angle; (B) foot-strike indicator; and (C) stride length.

4.8.3 MOTION OF THE BACK

The orientation of the back during the period from front foot contact until ball release was also calculated. These angles were first normalised using the neutral position of the subject (see Section 3.4) using a direction cosine matrix (Appendix 5). This accounted for differences in the marker positions between bowlers and defined the neutral posture of each bowler to correspond to upper and lower-back angles of (0°, 0°, 0°). The upper and lower-back angles were calculated at the instants of front foot contact and ball release. The amount of flexion and extension occurring at both joints, about the three local coordinate axes, were also calculated for this period. The peak lower-back extension, contralateral side-side flexion and ipsilateral rotation occurring between front foot contact and ball release were recorded for each trial.

4.8.4 POSITION OF THE BOWLING ARM

The position of the bowling arm at ball release was described using the x-component of the shoulder angle at the instant of ball release. This corresponds to the orientation of the upper arm relative to the local reference frame of the upper back (Figure 4.7). The ball release height was defined as the height of the marker on the ball, in the global z-direction,
at the instant of ball release. Ball release height was normalised using the bowler’s standing height, allowing comparison between bowlers.

Figure 4.7 – The measured shoulder angle at release and ball release height.

4.8.5 CRICKET SPECIFIC PARAMETERS

The lines of the shoulders and pelvis were defined to be a line joining their respective joint centres, which were then projected onto the global x-y plane (Figure 4.8A). As in previous studies, a fully side-on bowler was defined to have a shoulder (and pelvis) projection angle of 180°, whereas a fully front-on bowler had a shoulder projection angle of 270°. The shoulder projection angle was calculated at the instant of back foot contact, the angle between the shoulder and pelvis projections was also calculated at this instant. A positive pelvis-shoulder separation angle indicated the shoulders were more front-on than the pelvis. The minimum pelvis-shoulder separation angle between back foot contact and ball release was also calculated for each trial. The amount of shoulder-counter rotation was the change in shoulder projection angle from the instant of back foot contact to the most side-on orientation during the delivery stride. Similarly, the shoulder forwards-rotation was the change in shoulder angle from the most side-on orientation until the instant of ball release. The angle of lean-back was the angle between the global z-axis and a line joining the ankle
joint centre on the back foot and the mid-point between the shoulder joint centres when projected onto a global y-z plane (Figure 4.8B).

![Figure 4.8](image)

**Figure 4.8** – Illustrations of: (A) the projection angle of the shoulders and pelvis at back foot contact (viewed from above); (B) the lean back angle.

### 4.8.6 KINETIC PARAMETERS

Descriptive parameters for the ground reaction forces during the front foot contact phase were calculated using the force data collected within Kistler’s Bioware software. These parameters included the peak force in both the horizontal (braking) and vertical directions and the time from front foot contact till the occurrence of these peak forces. This information enabled the peak horizontal loading rate (PHLR) and peak vertical loading rate (PVLR) to be calculated – the average rate of loading. The impulse generated during the period from front foot contact was also calculated, in both the horizontal and vertical directions.

Forces and moment acting at each joint within the 18 segment system were estimated using the inverse dynamics calculations performed within the BodyLanguage code. This enabled the peak resultant force acting at the base of the lumbar spine (lower-back segment) to be
calculated as well as the time from front foot contact until the occurrence of this peak. Unfortunately, the moments calculated were very noisy during the initial part of the front foot contact phase and were not removed even when both the kinetic and kinematic input data were filtered heavily (Figure 4.9). It is believed these oscillations may be introduced when a system with pin-joints is used to analyse an impact. The system is unable to account for the change in the position of the point of contact between bones that occurs at a joint when the joint angle is changed. It was possible, however, to estimate the moment acting at each joint by taking an average value once the initial oscillations had subsided.

Figure 4.9 – An illustration of the oscillations observed in the flexion-extension moment of the front knee for filtered and unfiltered analogue data. (The period illustrated is from front foot contact until ball release)

4.9 STATISTICAL ANALYSIS

All statistical analyses were performed in Statistical Package for the Social Sciences v.17 (SPSS Corporation, USA). The variation observed in each parameter calculated (kinematic and kinetic) were assessed using an analysis of variance (ANOVA). The between-bowler variability (standard deviation of the observations) was compared with the between-trial variability. This ranged from 3.63 – 23.19% for the parameters calculated in
this study, corresponding to an intra-class correlation coefficient of 0.95 – 0.99. As there was good between-trial repeatability for all parameters, the three trials analysed were averaged to provide representative data for each bowler. Correlations were assessed using a two-tailed Pearson’s product moment coefficient. The effect of interactions between technique variables on a particular outcome measure were addressed using linear regression. As the data set in this study was relatively small, a maximum of four variables were included in any predictive equation with the requirement for the inclusion of a variable being $P < 0.10$.

4.10 CHAPTER SUMMARY

This chapter has described the 18 segment full-body inverse dynamics analysis performed and provided details regarding the individual segment definitions. The integration of the subject specific segmental parameters within the analysis was explained and details regarding the interpretation of the output parameters provided. Calculations used to calculate descriptive variables for each trial were outlined and the use of a mean value as a representative measure for each bowler justified. Additional information was also provided regarding the statistical methods used to generate the results found in subsequent chapters.
This chapter provides an overview of the fast bowling action and details of the technique variation displayed in the group of twenty elite bowlers involved in this study. Key variables previously considered in the literature are reported, in addition to a number of new variables introduced in the current study. The second half of the chapter addresses a range of questions regarding relationships between bowling technique, ball speed and ground reaction forces which have been reported / proposed in the literature.
5.1 THE FAST BOWLING ACTION

The fast bowling action can be considered to consist of two phases: i) the run-up and back foot contact phase; ii) the front foot contact phase (Figure 5.1). The techniques used by the subjects in this study during these two phases will be reported. The group of twenty elite fast bowlers in this study had ball release speeds in the range $32.80 - 39.72 \text{ m.s}^{-1}$ or $73.4 - 88.9 \text{ mph}$ (mean $34.94 \pm 1.67 \text{ m.s}^{-1}$).

![Figure 5.1](image)

**Figure 5.1** – The fast bowling action – (A) Run-up; (B-D) Back foot contact; (E-I) Front foot contact; (J) Follow through.
5.1.1 THE RUN-UP AND BACK FOOT CONTACT PHASE

Just prior to the instant of back foot contact, the bowlers had a run-up speed of 4.77 – 6.76 m.s\(^{-1}\) (mean 5.79 ± 0.58 m.s\(^{-1}\)). This range of run-up speeds is similar to those reported in previous studies in the literature. As their back foot made contact with the ground, all except one of the bowlers were leaning backwards slightly (Figure 5.1B); this angle of lean back ranged from -3.39 – +17.02° (mean 9.02 ± 5.22°). The shoulder alignment angle at back foot contact (Figure 5.2) was used to classify bowling actions as either: side-on (< 210°); mid-way (210 – 240°); or front-on (> 240°) – this classification system is described in detail in Section 2.1. In the current study, the shoulder alignment angle at back foot contact ranged from 211.5 – 253.1° (mean 231.5 ± 13.7°); six of the bowlers were front-on and the remaining fourteen were mid-way.

(A) (B)

Figure 5.2 – An illustration of the shoulder alignment angle at back foot contact for: (A) the most side-on bowler; (B) the most front-on bowler in this study.
The separation angle between the lines of the pelvis and shoulders at the instant of back foot contact is one measure used to identify bowlers with a mixed action (Figure 5.3). A bowler is classified as having a mixed action if this angle exceeds 30°. In this study, the pelvis-shoulder separation angle at back foot contact ranged from $-18.1$ to $+34.6°$ (mean $12.2 \pm 12.5°$), exceeding 30° for just one bowler. A positive pelvis-shoulder separation angle indicates a bowler’s shoulders are more front-on than their pelvis.

Figure 5.3 – An illustration of the pelvis-shoulder separation angle at back foot contact.
Once the back foot is on the ground, bowlers twist their shoulders back relative to their pelvis (shoulder counter-rotation) and stretch out their front leg in preparation for front foot contact (Figure 5.4). The amount of shoulder counter-rotation is another measure used to identify bowlers with a mixed action. A bowler’s action is defined to be mixed if they have more than 30° of shoulder counter-rotation. The bowlers in this study had shoulder counter-rotation angles in the range 9.8 – 65.1° (mean 36.7 ± 14.1°). Fourteen of the twenty bowlers tested had more than 30° of shoulder counter-rotation, with even the mean amount of shoulder counter-rotation for this group exceeding the current threshold for a mixed action.

Figure 5.4 – Illustration of a bowler counter-rotating their shoulders and extending their front leg during the back foot contact phase.

The peak (minimum) pelvis-shoulder separation angle ranged from -63.3 – -27.5° (mean -39.6 ± 9.6°). For all but two of the bowlers tested, this occurred just after the instant of front foot contact. The mean time from front foot contact until peak pelvis-shoulder separation angle was 0.031 ± 0.019 s (range -0.02 – +0.057 s). Using the current action classification system the bowlers were classified as: 6 x mid-way; and 14 x mixed. As reported by Ranson et al. (2008), all bowlers who had a front-on alignment at back foot contact had more than 30° of shoulder counter-rotation and were therefore classified as having a mixed bowling action.
5.1.2 FRONT FOOT CONTACT PHASE

The bowlers in this study had a stride length of 1.29 – 1.82 m (mean 1.47 ± 0.16 m), corresponding to a range of 69.1 – 92.4% (mean 78.5 ± 7.2%) of their standing height. The two-dimensional plant angle at the instant of front foot contact ranged from 27.3 – 43.0° (mean 36.3 ± 3.9°). The motion of the front knee during the front foot contact phase has been linked to both the dissipation of ground reaction forces and ball release speed in previous studies (Portus et al., 2004). All of the knee action classifications defined by Portus et al. (2004) (Figure 5.5) were represented in this group of bowlers: 9 x flexor extender; 6 x flexor; 3 x extender; and 2 x constant brace. Interestingly, the flexor-extender technique was far more prevalent than observed by Portus et al. (2004) who reported just 4/42 bowlers used this technique, with the flexor technique being the most prevalent (25/42). This is likely to be partly attributable to the higher spatial and temporal resolution of the motion data used in the current study or perhaps the standard of the bowlers tested.

![Figure 5.5A](image1.png) – The flexor front leg technique.

![Figure 5.5B](image2.png) – The extender front leg technique.
Figure 5.5C – The flexor-extender front leg technique.

Figure 5.5D – The constant brace front leg technique.

The knee angle (flexion / extension) at front foot contact and ball release ranged from 148.3 – 172.7° (mean 164.1 ± 6.1°) and 120.3 – 186.2° (mean 167.3 ± 18.8°), respectively. On average the bowlers flexed their knee by 17.5 ± 11.2° and extended it by 11.9 ± 7.4° in the period between front foot flat and ball release. Two of the bowlers had less than 1° of flexion, these bowlers also had the most hyper-extended front knees at ball release. Six of the twenty bowlers tested had less than 6° of knee extension. As discussed in Chapter 4, it was not possible to remove the initial oscillations from the moments calculated using inverse dynamics. However, they did indicate that bowlers were typically exerting an extensor moment in the region of 200 N.m about the flexion-extension axis of the front knee during the front foot contact phase.

The angle of the front hip (flexion / extension) at front foot contact ranged from 117.3 – 148.8° (mean 133.0 ± 9.3°) and was in the range 99.8 – 140.0° (mean 117.3 ± 10.5°) at ball release. Within the group of bowlers tested, the manner of foot-strike at front foot contact varied: 13 were heel strikers and 7 were mid-foot / forefoot strikers. The value of the calculated foot-strike indicator ranged from -30.8 – +11.0° (mean -8.24 ± 13.2°), with the most negative values corresponding to the most plantar-flexed bowlers at front foot contact.
This corresponded to an anatomical ankle angle of 103.9 – 150.4° (mean 126.3 ± 13.8°) at the instant of front foot contact.

![Figure 5.6](image)

**Figure 5.6** – An illustration showing the bowlers with the most dorsi-flexed (A) and most plantar-flexed (B) foot at the instant of front foot contact.

Ground reaction forces varied widely among the bowlers tested in this study. Peak vertical ground reaction forces ranged from 3.99 – 8.63 BW (mean 6.72 ± 1.42 BW) and peak braking forces were in the range 2.55 – 6.05 BW (mean 4.47 ± 0.75 BW). Previously reported peak vertical ground reaction forces during the front foot contact phase have been similar, 3.8 – 9.0 BW (details provided in Section 2.3). The peak braking forces are higher than those reported in the past (1.4 – 4.5 BW), previous studies observing relatively high peak braking forces (3.54, 4.5 BW). Hurrion *et al.*, (2000) suggested this may be due to higher approach speeds, bowling technique, or the commitment and ease with which bowlers were able to perform within the confines of the testing procedure. The time from front foot contact until peak vertical force was in the range 0.009 – 0.050 s (mean 0.030 ± 0.012 s), the time to peak braking force was 0.018 – 0.046 s (mean 0.032 ± 0.009 s). Peak vertical loading rates ranged from 85.74 - 892.44 BW.s\(^{-1}\) (mean 309.47 ± 219.49 BW.s\(^{-1}\)) and peak horizontal loading rates were in the range 55.16 - 282.12 BW.s\(^{-1}\) (mean 153.88 ± 55.63 BW.s\(^{-1}\)).

Ranson *et al.* (2008) proposed that concurrent lower trunk extension, ipsilateral rotation and extreme contralateral side-flexion during the early phase of the front foot contact phase of the bowling action (Figure 5.7) may be an important mechanical factor in the aetiology of lumbar stress injuries.
In the current study, the mean peak orientation of the lower-back during this phase of the action were $0.4 \pm 4.5^\circ$ of flexion (maximum extension observed was $7.8^\circ$), $15.9 \pm 6.9^\circ$ side-flexion (maximum $31.7^\circ$), and $25.1 \pm 10.9^\circ$ of rotation (maximum $39.9^\circ$). The inverse dynamics analysis performed enabled the peak forces in the lower back to be estimated during this phase, the mean peak resultant force at the base of the lower back was $5.41 \pm 1.35$ BW.

The amount of shoulder forwards-rotation up to the instant of ball release ranged from $80.6$ – $143.4^\circ$ (mean $115.5 \pm 18.2^\circ$). The upper arm angle, relative to the local x-coordinate axis of the upper-back, was $-72.0$ – $+4.9^\circ$ at the instant of front foot contact. All but two of the bowlers’ upper arm were behind the line of the upper-back at front foot contact, the average position was $-28.8 \pm 22.1^\circ$. At the instant of ball release the mean shoulder angle was $-140.6 \pm 15.3^\circ$ (range $-173.1$ – $-102.4^\circ$), all bowlers had their upper arm behind the line of the upper back at ball release (Figure 5.8). The ball release height ranged from $1.91$ – $2.27$ m (mean $2.12 \pm 0.10$ m), when normalised this became $105.4$ – $121.6\%$ (mean $112.8 \pm 4.1\%$) of the bowler’s standing height.

**Figure 5.7** – The posture of a bowler early in the front foot contact phase.
5.2 QUESTIONS BASED ON THE LITERATURE

A number of previous studies have attempted to identify links between aspects of fast bowling technique, ball release speed and ground reaction forces. However, none have collected synchronous three-dimensional kinematic and kinetic data for a group of elite fast bowlers. In this section, nine questions are posed and addressed using the data collected in this study using Pearson’s correlation coefficients. The results are discussed in the light of previous reported / proposed relationships in the literature.

1. Do bowlers with a faster run-up release the ball at higher speeds?

A significant positive correlation was observed between run-up speed and ball release speed for the data in the current study (r = 0.499, P = 0.025). This supports the work of Glazier et al. (2000) as well as Elliott and Foster (1989); bowlers with a quicker run-up have more linear momentum which can potentially be converted into ball speed. There is likely to be an optimum run-up speed, beyond which ball release speed decreases (as observed by Brees, 1989) as bowlers are unable to coordinate the technique required to control the additional run-up speed. Unsurprisingly, this was not identifiable in data collected in this investigation, as all subjects were elite bowlers performing maximum pace deliveries.
2. Do front-on bowlers run-up faster or release the ball at higher speeds than more side-on bowlers?

Previous suggestions that front-on bowlers are able to run-up faster and contribute more of their horizontal velocity to the ball release speed than side-on bowlers (Elliott and Foster, 1984; Bartlett, 1992) were not supported by the data collected in this study. Although no bowlers were side-on, there was no evidence of a correlation between the shoulder projection angle at back foot contact (the variable used to classify bowling action type) and either run-up speed (r = 0.112, P = 0.638) or ball release speed (r = 0.311, P = 0.182). These findings concur with those of Stockill and Bartlett (1992a).

3. Is the amount of lean-back at back foot contact linked to ball release speed?

The MCC (1976) state that a bowler’s weight should be on the back foot, leaning away from the batsman, at back foot contact. This is similar to some javelin throwing techniques and has been suggested to increase the acceleration path of the ball (Bartlett and Best, 1988). The data collected in the current study did not indicate a correlation between the amount of lean-back at back foot contact and ball release speed (r = 0.117, P = 0.624). However, all except two of the bowlers were leaning back at this point in the action (mean 9.02 ± 5.22°). This suggests it may be beneficial to be leaning back at the instant of back foot contact, but does not identify a relationship between the amount of lean-back and ball release speed.

4. Is ball release speed linked to either the front knee angle at front foot contact or its change during the front foot contact phase?

In agreement with Burden and Bartlett (1990b), a significant correlation was observed between ball release speed and a more extended front knee at both front foot contact (r = 0.492, P = 0.027) and ball release (r = 0.512, P = 0.021). It has been suggested that a front knee which extends, or remains extended, during the front foot contact phase may permit a more efficient transfer of kinetic energy to the ball and facilitate a higher release speed (Elliott et al., 1986; Portus et al., 2004). However, in the current study there is no evidence of a significant correlation between ball release speed and either the amount of
knee flexion (r = -0.247, P = 0.294) or knee extension (r = 0.365, P = 0.114) between front foot contact and ball release. The mild correlation (r = 0.365) between knee extension and ball release speed was almost significant for the sample of bowlers in this study, suggesting there may be a relationship present. This will be considered in more detail in Chapter 6, where the effect of interactions between technique parameters on ball release speed are considered.

5. Are the shoulder alignment and pelvis-shoulder separation angle linked to ball release speed?

The amount of shoulder forwards-rotation prior to ball release was significantly correlation with ball speed in the current study (r = 0.389, P = 0.090). A significant correlation was also observed between the minimum pelvis-shoulder separation angle and ball release speed (r = -0.529, P = 0.016); bowlers whose shoulders wound back more relative to their pelvis typically bowled faster. As reported by Portus et al. (2004) the amount of shoulder counter-rotation did not appear to be linked to ball release speed (r = 0.298, P = 0.202). There was also no evidence of a correlation between ball speed and either the pelvis-shoulder separation angle at back foot contact (r = -0.004, P = 0.986), or the timing of the minimum pelvis-shoulder separation relative to the instant of front foot contact (r = 0.182, P = 0.442). These results would appear to suggest the quickest bowlers are those who increase the amount of shoulder forwards-rotation they can achieve by means of a large pelvis-shoulder separation angle.

6. Is the motion of the thorax (upper-back segment) during the front foot contact phase related to the speed at which the ball is released?

Davis and Blanksby (1976b) and Elliott et al. (1986) estimated that trunk flexion contributes 11% and 13%, respectively, of the final ball release speed. Burden and Bartlett (1990a) reported differences in trunk flexion angles between bowlers releasing the ball at different speeds, were between front foot contact and ball release. This was not supported with the data from the current study, no correlation was observed between ball speed and: thorax angle at front foot contact (r = 0.006, P = 0.981); thorax angle at ball release (r = -0.297, P = 0.203); or the amount of flexion of the thorax between front foot contact and
ball release ($r = 0.251, P = 0.287$). These results, however, are based on the angle between the upper and lower-back segments, not relative to the global coordinate system, which may account for the lack of evidence supporting previous reported relationships.

Interestingly, a significant correlation was observed between ball release speed and the amount of side-flexion during the period from front foot contact until ball release ($r = -0.396, P = 0.084$); bowlers who side flexed more released the ball at faster speeds. This is potentially of concern as higher peak side-flexion during the front foot contact phase have been suggested to be linked to the high rate of lower back injuries on the non-dominant side seen in fast bowlers (Ranson et al., 2008).

7. Are ball release speeds linked to the position of the arm at ball release or the ball release height?

Ball release speed was significantly correlated with both the shoulder angle (flexion / extension) at ball release ($r = 0.389, P = 0.090$) and the normalised ball release height ($r = -0.599, P = 0.005$) in the current study. In apparent contradiction with a number of studies (Elliott et al., 1986; Burden and Bartlett, 1989; Foster et al., 1989; Burden, 1990) the fastest bowlers’ arm was further back (relative to the upper-back) at ball release. Again this may be because joint angles are being considered in the current study as opposed to the orientation relative to the global coordinate system. This observed correlation between ball speed and shoulder angle at release, however, may be indicative of the use of a proximal to distal sequencing within the bowling action - driving initially with the thorax and the arm motion following. This would tie in with beliefs among coaches, where it is said that the fastest bowlers have a smooth and rhythmical action as opposed to using an extreme effort.

The link between a lower normalised release height and faster ball speeds contradicts the intuitive belief that a higher release position enables higher release speeds. It is unlikely that a low release height, in itself is beneficial, it therefore seems plausible that a low release height may be a consequence of other aspects of technique which are themselves linked to ball release speed. The interaction between technique parameters and ball release speed will be investigated more thoroughly in Chapter 6.
8. Are faster ball release speeds associated with higher ground reaction forces and loading rates?

In the current study, ball release speed was observed to be correlated with lower peak loading rates in both the vertical ($r = -0.452$, $P = 0.046$) and horizontal directions ($r = -0.484$, $P = 0.031$). A correlation was also noted between ball release speed and smaller peak vertical forces, however, this was not significant in the sample of bowlers tested ($r = -0.364$, $P = 0.114$). These results strongly contradict the findings of Portus et al. (2004) who found higher peak breaking forces and loading rates (both vertically and horizontally) were linked to faster ball release speeds. Interestingly, the ground reaction force characteristic most strongly correlated with ball speed was the horizontal impulse until ball release ($r = 0.574$, $P = 0.008$), a variable not previously considered in the literature. This will be the focus of Chapter 8.

9. Does knee flexion during the front foot contact phase reduce peak ground reaction forces and loading rates?

The use of a technique in which the front knee flexes during the front foot contact phase was recommended by Foster et al. (1989), in order to dissipate ground reaction forces and reduce the likelihood of injury. Portus et al. (2004) observed that bowlers with an extended / extending front knee had higher peak ground reaction forces and that these forces were also developed more rapidly. The data in the current study does not support these observations (Table 5.1). The lack of evidence supporting these previously reported relationships are perhaps indicative of the multi-factorial nature of the relationship between fast bowling technique and ground reaction forces. These interrelationships will be investigated in more detail in Chapter 7.
Table 5.1 – Correlations between ground reaction force characteristics and parameters describing the motion of the front knee during the front foot contact phase $(r, P)$.

<table>
<thead>
<tr>
<th>GRF Properties</th>
<th>Knee Angle at Front Foot Contact</th>
<th>Knee Flexion – Front Foot Flat till Ball Release</th>
<th>Knee Extension – Front Foot Flat till Ball Release</th>
<th>Knee Angle at Ball Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Vertical Force</td>
<td>0.207, 0.382</td>
<td>0.006, 0.980</td>
<td>-0.034, 0.885</td>
<td>-0.056, 0.814</td>
</tr>
<tr>
<td>Peak Braking Force</td>
<td>0.185, 0.435</td>
<td>-0.112, 0.639</td>
<td>0.311, 0.183</td>
<td>0.195, 0.409</td>
</tr>
<tr>
<td>PVLR</td>
<td>0.248, 0.292</td>
<td>0.046, 0.849</td>
<td>-0.161, 0.498</td>
<td>-0.159, 0.502</td>
</tr>
<tr>
<td>PHLR</td>
<td>0.236, 0.316</td>
<td>-0.034, 0.885</td>
<td>-0.054, 0.823</td>
<td>-0.108, 0.650</td>
</tr>
</tbody>
</table>

5.3 CHAPTER SUMMARY

This chapter has provided an overview of the components of the fast bowling action and provided details regarding the techniques adopted by the subjects tested in this study. A number of questions, based on relationships discussed in previous literature, were also addressed using the data collected in this study. The following four chapters are in the form of papers, each paper address one of the research questions posed in Chapter 1.
6.1 ABSTRACT

Ball release speed is a major contributor to fast bowling success and has been the focus of a number of previous investigations. These studies have identified individual aspects of fast bowling technique which characterise the fastest bowlers. However, none have accounted for interactions between technique variables. The aim of this investigation was to identify the key aspects of technique which characterise the fastest bowlers and to consider the mechanics behind these relationships. Data were collected for a group of twenty elite fast bowlers, each performing six maximum pace deliveries of good length in an indoor practice facility. Three dimensional kinematic data were collected using an 18 camera Vicon Motion Analysis System. Forty-seven 14 mm retro-reflective markers were attached to each subject; an additional marker was attached to the ball to enable ball release speed and the instant of ball release to be determined. All marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz. Eleven kinematic parameters were determined for each trial, describing elements of fast bowling technique which have previously been linked to ball release speed. The effect of interactions between technique variables on ball release speed were addressed using linear regression. Four technique variables were identified as being the best predictors of ball release speed, explaining 73.6% of the observed variation in ball release speed. The results suggest that the fastest bowlers have a quicker run-up and maintain a straighter knee throughout the front foot contact phase. The fastest bowlers were also observed to exhibit larger amounts of thoracic flexion up to ball release and appeared to delay the onset of upper arm circumduction. The results of this investigation are likely to be very useful in the coaching of fast bowling and in talent identification among young bowlers. Future studies should address the effect of technique changes for individual bowlers, enabling optimum techniques to be identified.
6.2 INTRODUCTION

Ball release speed is a major contributor to fast bowling success as it reduces the time the batsman has to interpret the path of the ball and make decisions regarding which shot to play. The quickest bowlers release the ball at speeds in excess of 90 mph. An understanding of the mechanics of how bowlers generate ball speed, in addition to a knowledge of those aspects of technique which best predict fast release speeds, would be extremely beneficial to the coaching of fast bowling. A number of previous studies have sought to identify individual elements of fast bowling technique which characterise the fastest bowlers, the findings of these studies are summarised below.

A strong correlation between run-up speed, during the pre-delivery stride, and ball release speed ($r = 0.728$, $P < 0.05$) was reported by Glazier et al. (2000). This ties in with the suggestion of Elliott and Foster (1989) that run-up speed should be sufficient to produce as high a linear velocity of the body as possible, whilst enabling the correct delivery technique to be adopted.

Other studies have investigated relationships between ball release speed and the motion of the front knee during the front foot contact phase of the bowling action. Burden and Bartlett (1990b) observed that faster ball release speeds were associated with a more extended front knee at the instant of ball release ($r = 0.41$). Portus et al. (2004) considered the motion of the front knee during the period from full foot contact (front foot flat) until ball release. They observed that faster ball release speeds were associated with larger amounts of knee extension in this period ($r = 0.37$, $P = 0.02$). It has been suggested that a front knee which extends, or is already extended, during the front foot contact phase may permit a more efficient transfer of energy to the ball and facilitate faster ball release speeds (Elliott et al., 1986; Portus et al., 2004). However, there is currently no firm agreement regarding the importance of the motion of the front knee in determining ball release speed.

Action type (front-on, mid-way, side-on) was observed not to be linked to ball release speed (Stockill and Bartlett, 1992b), nor was the amount of shoulder counter-rotation ($r = 0.009$, $P = 0.95$) (Portus et al., 2004). However, Portus et al. (2004) did observe a correlation between ball release speed and the timing of the maximum pelvis-shoulder separation angle during the delivery stride. Those bowlers whose maximum separation angle occurred later in the delivery action (relative to the instant of front foot contact) bowled faster ($r = 0.34$, $P = 0.05$). Similarly, Tyson (1976) suggested the position of the
arm at front foot contact was a good predictor of release speed, with faster bowlers delaying the onset of upper arm circumduction. However, no subsequent research has been identified as supporting this (Bartlett et al., 1996).

A link between the amount of shoulder girdle rotation (shoulder forwards-rotation) preceding ball release and bowling speed (r = 0.30, P = 0.05) was reported by Portus et al. (2004). Increased flexion of the trunk between front foot contact and ball release has also been reported to provide a significant contribution to ball release speed (Burden and Bartlett, 1990a). It has been estimated that trunk flexion contributes 11-13% of the final ball release speed (Davis and Blanksby, 1976b; Elliott et al., 1986).

A number of studies have identified links between the position of the arm (and ball) at the instant of ball release. Faster bowlers have been reported to release the ball with the arm further out in front of the line of the trunk (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1989; Foster et al., 1989; Burden, 1990).

Currently there is no consensus regarding which aspects of bowling technique are the best indicators of fast ball release speeds. As has been described, a wide variety of different elements of technique have been reported to be linked to ball release speed by previous investigators. The aim of the current study was to identify the key aspects of technique characterising the fastest bowlers and to address the mechanics behind the generation of ball speed.

6.3 METHODOLOGY

6.3.1 PARTICIPANTS

Twenty elite fast bowlers (mean ± standard deviation: age 20.1 ± 2.6 years; height 1.88 ± 0.08 m; body mass 81.5 ± 7.1 kg) participated in this investigation. Each bowler performed six maximum velocity deliveries of good length which were recorded using an 18 camera Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 300 Hz. Data were collected in an indoor cricket facility (Figure 6.1); bowlers used a full length run-up on a standard sized artificial cricket pitch. All bowlers were identified as “fast-bowlers” by ECB (England and Wales Cricket Board) fast bowling coaches and were deemed fit to bowl by their County Physiotherapist. The testing procedures were
explained to each subject in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All subjects conducted a thorough warm-up prior to commencing data collection.

Figure 6.1 – The data collection environment.

6.3.2 DATA COLLECTION

Forty-seven retro-reflective 14 mm markers were attached to each subject (Figure 6.2), positioned over bony landmarks in accordance with a marker set developed specifically for the analysis of fast bowling techniques. An additional marker, in the form of a 15 x 15 mm patch of 3M Scotch-Lite reflective tape, was attached to the ball to enable ball release speed and the instant of ball release to be determined. Static and range of motion (ROM) trials were performed for each subject, allowing body segment lengths and a neutral spine position to be calculated (using the methodology of Ranson et al., 2008). Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990) enabling subject-specific segmental inertia parameters to be determined for each bowler.
6.3.3 DATA PROCESSING

The best three bowling trials, maximum velocity deliveries with minimal marker loss, were identified for each bowler. These trials were manually labelled and processed using the Vicon Workstation and BodyBuilder software (OMG Plc, Oxford, UK). The instants of back foot contact, front foot contact and front foot flat were manually identified, using the motion of the markers on the foot. Ground contact was defined to be the first frame in which the motion of the foot was observed to change due to contact with the ground. Front foot flat corresponded to the first frame in which the forefoot was on the ground. The instant of ball release was identified using the time-history of the distance between the marker on the ball and the mid-point of a pair of markers placed over the wrist. All marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz.

Joint centres were calculated from a pair of markers placed across each joint, positioned such that their mid-point coincided with the corresponding joint centre. The hip joint centres were calculated using the “hip joint centring algorithm” (Davis et al., 1991) from markers placed over the left and right anterior superior iliac spine and the left and right posterior superior iliac spine. Lower and upper back motions were defined using the four markers on the pelvis in addition to markers placed over the proximal (sterna) and distal (clavicular) ends of the sternum as well as the spinous processes of L1, T10 and C7.
Local reference frames were defined comprising a three-dimensional full-body 18 segment representation of a bowler. These segments were: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two-segment foot. A local coordinate system was defined for each segment using three markers on the segment itself. This allowed segment orientations and joint angles to be calculated. The origin of each reference frame was located at the lower joint centre of the segment when the bowler stood in the anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the subject’s right (flexion-extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with the y-axis pointing down the wicket, the x-axis pointing to the right and the z-axis representing the upwards vertical.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using an xyz sequence – representing an initial rotation about the x-axis of the parent, followed by rotation about a floating y-axis of the parent and finally the z-axis of the child. These rotations corresponded to flexion-extension, abduction-adduction or varus-valgus rotation, and longitudinal rotation, respectively.

6.3.4 KINEMATIC DATA REDUCTION

Eleven kinematic parameters were calculated for each trial, describing elements of fast bowling technique which have previously been linked to ball release speed in the literature. These parameters were:

- run-up speed (horizontal)
- knee angle at front foot contact and ball release
- knee flexion and extension (front foot flat till ball release)
- shoulder forwards rotation
- thoracic flexion (front foot contact till ball release)
- shoulder angle at front foot contact and ball release
- minimum pelvis-shoulder separation angle and its timing relative to front foot contact
Angles describing the front knee (straight = 180°), thorax (straight = 0°) and shoulder (anatomical position = 0°) (Figure 6.3) corresponded to the anatomical flexion / extension angle of the joint calculated using the 18-segment representation. The orientation angle of the thorax (upper back segment) was normalised using a neutral position of the spine determined from the range of motion trial captured (using the methodology of Ranson et al., 2008). An upright position of the thorax (upper back) was defined to correspond to an angle of 0°, 0°, 0° about the x, y and z-axes of the lower back segment.

**Figure 6.3** – Illustration of the shoulder angle calculated at ball release. (The bowler shown has a shoulder angle of 195°).

The alignment of the shoulders and pelvis were calculated by projecting their respective joint centres onto a horizontal plane (Figure 6.4). A bowler facing directly down the wicket was defined to have a shoulder and pelvis projection angle of 270°, standing in a purely side-on position corresponded to a projection angle of 180°. Shoulder forwards-rotation was defined as the change in shoulder projection angle from the most side-on position to the orientation at ball release. The pelvis-shoulder separation angle was calculated by subtracting the pelvis projection angle from the shoulder projection angle. The minimum pelvis-shoulder separation angle was calculated for each trial, in addition to the timing of this instant relative to the instant of front foot contact.
Figure 6.4 – The pelvis and shoulder projection angles for a bowler at back foot contact.

The horizontal run-up speed (in the global y-direction) was determined using the calculated position of the centre of mass, from the 18-segment representation of the bowler. It was assumed the centre of mass moved with a constant horizontal velocity during the period of 18 frames (0.060 s) prior to the instant of back foot contact. Ball release speed was determined in a similar manner, using the motion of the marker on the ball during a period of 10 frames (0.033 s) from the instant of ball release. A constant velocity was assumed in the global x and y-directions, constant acceleration equations were used to calculate the vertical velocity at ball release.

6.3.5 STATISTICAL ANALYSIS

All statistical analysis was performed within Statistical Package for the Social Sciences v.17 (SPSS Corporation, USA). The variation observed in each technique parameter (including ball speed) were assessed using an analysis of variance (ANOVA). The between-bowler variability (standard deviation of the observations) was compared with the standard deviation of the between-trial variability. This ranged from 8.33 – 22.46% (mean 13.25%) for the parameters calculated in this study, corresponding to an intra-class correlation coefficient of 0.95 – 0.99 (mean 0.98). As there was good between-trial repeatability for all technique parameters, the three trials analysed were averaged to provide representative data for each bowler. The effect of interactions between technique variables on ball release speed were addressed using linear regression. A maximum of
four variables were included in the predictive equation with the requirement for the inclusion of a variable being $P < 0.10$.

### 6.4 RESULTS

The twenty elite fast bowlers participating in this study had ball release speeds of $32.80 - 39.72$ m.s$^{-1}$ ($34.94 \pm 1.67$ m.s$^{-1}$). Six of these bowlers had a front-on shoulder alignment at back foot contact and the remaining fourteen were mid-way (using the definitions described by Portus et al., 2004). Using the front knee technique classification system introduced by Portus et al. (2004), the bowlers were classified as: 9 x flexor-extender; 6 x flexor; 3 x extender; and 2 x constant-brace. Details of the range, mean and standard deviation of each calculated technique parameter for the group of bowlers are provided in Table 6.1.

**Table 6.1** – Details of the range, mean and standard deviation of each technique parameter calculated for the group of bowlers.

<table>
<thead>
<tr>
<th>Technique Variable</th>
<th>Range</th>
<th>Mean (Standard Deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-up speed (m.s$^{-1}$)</td>
<td>4.77 – 6.76</td>
<td>5.79 ± 0.58</td>
</tr>
<tr>
<td>Knee angle at front foot contact (°)</td>
<td>148.3 – 172.7</td>
<td>164.1 ± 6.1</td>
</tr>
<tr>
<td>Knee angle at ball release (°)</td>
<td>120.3 – 186.2</td>
<td>167.3 ± 18.8</td>
</tr>
<tr>
<td>Knee flexion from front foot flat till ball release (°)</td>
<td>0.0 – 44.8</td>
<td>17.5 ± 11.2</td>
</tr>
<tr>
<td>Knee extension from front foot flat till ball release (°)</td>
<td>0.3 – 26.3</td>
<td>11.9 ± 7.4</td>
</tr>
<tr>
<td>Shoulder forwards-rotation (°)</td>
<td>80.6 – 143.4</td>
<td>115.5 ± 18.2</td>
</tr>
<tr>
<td>Thoracic flexion from front foot contact till ball release (°)</td>
<td>11.2 – 50.6</td>
<td>31.0 ± 8.3</td>
</tr>
<tr>
<td>Shoulder angle at front foot contact (°)</td>
<td>-72.0 – 5.0</td>
<td>-28.8 ± 22.1</td>
</tr>
<tr>
<td>Shoulder angle at ball release (°)</td>
<td>-173.1 – -102.4</td>
<td>-140.6 ± 15.3</td>
</tr>
<tr>
<td>Min pelvis-shoulder separation (°)</td>
<td>-63.3 – -27.5</td>
<td>-39.6 ± 9.6</td>
</tr>
<tr>
<td>Timing of minimum pelvis-shoulder separation (s)</td>
<td>-0.020 – 0.057</td>
<td>0.031 ± 0.019</td>
</tr>
</tbody>
</table>

The best individual predictor of ball release speed was the shoulder angle at the instant of ball release, explaining 30.3% of the variation in ball release speed (Table 6.2). An upper arm which was further back at ball release, relative to the line of the thorax (upper back),
was indicative of the quickest bowlers. The use of two technique parameters in the predictive equation increased the percentage variation explained to 57.7%, those parameters being the run-up speed and the knee angle at ball release. Faster ball release speeds were associated with a quicker run-up and a more extended front knee at ball release. Combining all three variables from these two predictive equations mentioned, into a three parameter function, explained 65.5% of the variation in ball speed. The highest percentage variation in ball speed was explained using four parameters: run-up speed; knee angle at ball release; thoracic flexion from front foot flat until ball release; and shoulder angle at front foot contact. This combination of parameters explained 73.6% of the variation in ball release speed. The quickest bowlers had more thoracic flexion between front foot contact and ball release and they also appeared to delay the onset of upper arm circumduction, indicated by a larger shoulder angle at front foot contact.

Table 6.2 – Details of the predictive equations produced using linear regression to explain ball release speed.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Parameter(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shoulder angle at ball release</td>
<td>0.060</td>
<td>0.012</td>
<td>30.3</td>
</tr>
<tr>
<td>2</td>
<td>Run-up speed Knee angle at ball release</td>
<td>1.683</td>
<td>0.002</td>
<td>57.7</td>
</tr>
<tr>
<td>3</td>
<td>Run-up speed Knee angle at ball release</td>
<td>1.623</td>
<td>0.002</td>
<td>65.5</td>
</tr>
<tr>
<td>4</td>
<td>Thoracic flexion from front foot contact until ball release</td>
<td>1.529</td>
<td>0.001</td>
<td>73.6</td>
</tr>
</tbody>
</table>

6.5 DISCUSSION

Previous studies have reported correlations between ball release speed and a variety of different elements of fast bowling technique. There is currently no consensus as to which aspects of technique are the most important in terms of determining ball release speed, nor has the mechanics of the generation of ball speed been discussed. This study used linear regression in order to account for interactions between technique parameters with the aim of identifying the key variables which determine ball speed. The results of this
investigation suggest the variation in ball speed observed among elite fast bowlers can be explained well using just four technique parameters (73.6% of the variation). These parameters were: run-up speed; shoulder angle at front foot contact; the amount of thoracic flexion between front foot contact and ball release; and the front knee angle at the instant of ball release.

The best individual predictor of ball release speed was the shoulder angle at the instant of ball release. The quickest bowlers had their upper arm further back relative to their thorax as they released the ball. Although this observed relationship does not particularly aid the understanding of the mechanics by which bowlers generate pace, it indicates the position the quickest bowlers adopt at ball release as a result of their technique during the delivery stride. A number of previous studies have reported a trend for quicker bowlers to release the ball with the arm “further out in front of the line of the trunk” (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1989; Foster et al., 1989; Burden, 1990). The results of the current study appear to strongly contradict these observations which could be attributable to the low frequency motion data (50 Hz) used in these previous studies or difficulty in identifying the instant of ball release. However, it is more likely that these previous researchers were referring to the orientation of the upper arm in relation to the vertical. The trend observed in the current study, for the fastest bowlers to have their upper arm further back relative to their thorax at the instant of ball release, suggests bowlers use thoracic flexion to generate ball speed. If the bowlers had generated the speed of their bowling arm using predominantly their shoulder muscles, they would be very unlikely to have their arm behind the line of the thorax at the instant of ball release.

In the predictive equation explaining the greatest percentage of the variation observed in ball release speed (4 technique parameters), the shoulder angle at ball release was replaced by two parameters. These were the shoulder angle at the instant of front foot contact and the amount of thoracic flexion during the period from front foot contact until ball release. This adds support to the suggestion that bowlers generate ball speed by thoracic flexion. These higher levels of thoracic flexion observed in the fastest bowlers are unlikely to be purely generated actively by bowlers, instead these bowlers appear to use an action which causes this increased flexion. This result also suggests that delaying the onset of upper arm circumduction (indicated by a larger shoulder angle at front foot contact) enables bowlers to release the ball at faster speeds. This trend for the quickest bowlers to delay the motion of their bowling arm was previously reported by Tyson (1976), but has not been reported
in any studies since. This is probably because the effect of the shoulder angle at front foot contact has been masked in previous studies by the effects of other aspects of technique.

A more extended front knee at ball release characterised the fastest bowlers. As a bowler plants their front leg at front foot contact, the linear momentum generated during their run-up is converted into angular momentum of their body about the front foot. The fastest bowlers use their front leg to rapidly slow the linear velocity of their pelvis, which in turn drives the thorax forwards about the pelvis. Bowlers who maintain a straight front knee throughout the front foot contact phase are able to perform this most efficiently. These bowlers can be identified as those who have the most extended front knee at the instant of ball release.

Run-up speed was also observed to be positively correlated with ball release speed, as reported by Glazier et al. (2000) as well as Elliott and Foster (1989). Bowlers with a quicker run-up have a greater amount of linear momentum which can potentially be converted into ball speed. There is likely to be an optimum run-up speed, beyond which ball release speed decreases (as observed by Brees, 1989), as bowlers are unable to coordinate the technique required to control the additional run-up speed. Unsurprisingly, this was not identifiable in the data collected in this study, which consisted of elite bowlers performing maximum velocity deliveries.

Small sample sizes are a common problem when studying elite populations. In the current study, the data set of twenty bowlers limited the number of technique parameters which could be confidently identified as explaining the variation in ball release speed to four. However, the 73.6% of variation in ball speed explained by the four parameter predictive equation suggests the key aspects of technique have been identified.

The results of this study represent relationships between bowling technique and ball release speed among a group of twenty elite fast bowlers. They indicate the key aspects of technique which differentiated bowling speeds within the group. Future studies should address the effect of changing aspects of technique on an individual. This would enable the effect of technique alteration to be addressed (such as what is the optimum run-up speed), in addition to the physical requirements (forces and moments) of these changes to technique.
6.6 CONCLUSIONS

This study has identified four characteristics of fast bowling technique which explain the majority of the variation in ball release speed observed among a group of elite fast bowlers. The results suggest that the quickest bowlers have a quicker run-up and maintain a straighter knee throughout the front foot contact phase. The fastest bowlers were also observed to exhibit larger amounts of thoracic flexion up to ball release and appeared to delay the onset of upper arm circumduction. The results of this investigation are likely to be very useful in the coaching of fast bowling and in talent identification among young bowlers. Future studies should address the effect of technique changes for individual bowlers, enabling optimum techniques to be identified and the mechanics of the generation of ball speed to be more thoroughly understood.
7.1 ABSTRACT

The most prevalent injuries among fast bowlers are lumbar stress fractures and lumbar injury on the non-dominant side of the body. Large ground reaction forces during the front foot contact phase of the bowling action are believed to be a major cause of these injuries. The aim of this study was to investigate the effect of the front leg technique used by fast bowlers on the ground reaction forces during the initial part of the front foot contact phase. Data were collected for a group of twenty elite fast bowlers, each performing six maximal velocity deliveries of good length in an indoor practice facility. Three dimensional kinematic data were captured using an 18 camera Vicon Motion Analysis System (300 Hz) and kinetic data for the front foot contact phase were collected using a Kistler force plate (1008 Hz). Forty-seven retro-reflective markers were attached to each subject; an additional marker was attached to the ball to enable ball release speed and the instant of ball release to be determined. All marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz. Eight kinematic parameters were determined for each trial, describing the run-up speed and front leg technique. Four kinetic parameters were also defined: peak forces in the vertical and horizontal directions; and the time from front foot contact until the occurrence of these peak forces. A representative value for each parameter was calculated for each subject – the mean value from the best three trials performed. The effect of interactions between technique variables on each of the four kinetic variables were addressed separately using linear regression. The results of this study suggest that the variation in peak force and time to peak force during the front foot contact phase can be explained using variables describing the initial orientation of the front leg at the instant of front foot contact. In contrast to suggestions in previous studies, it would appear the flexion of the front knee, during the front foot contact phase, occurring in the majority of bowlers is as a consequence of the high peak ground reaction forces. To understand the mechanics of these relationships in more detail, future studies should investigate the effect of changes to front leg technique on the ground reaction forces for individual bowlers.
7.2 INTRODUCTION

Cricket is generally considered to be a relatively low-injury sport, with only around five percent of elite players being unavailable to play due to injury at any given time (Newman, 2003). Fast bowlers, however, have similar injury rates to those reported for contact sports such as Australian rules football and the Rugby football codes (Orchard et al., 2006). The most prevalent injuries among fast bowlers are lumbar stress fractures and lumbar injuries on the non-dominant side (Newman, 2003).

Large peak ground reaction forces during the front foot contact phase of the fast bowling action are believed to be a major cause of these lower back injuries (Bartlett et al., 1996). These high peak forces coincide with the period of the action in which lower trunk movements known to produce high contralateral facet joint contact forces occur (lower trunk extension in conjunction with contralateral side-flexion and ipsilateral rotation). Portus et al. (2004) noted a trend for bowlers who have suffered a lower back stress fracture to have a faster rate of peak force development (both vertical and braking) during the front foot contact phase. These trends, however, were not significant in the group of bowlers tested. Peak ground reaction forces during the front foot contact phase vary widely among bowlers. There is currently limited research addressing the reasons for these differences.

Previous studies have reported mean peak ground reaction forces during the front foot contact phase in the range 3.8 – 9.0 bodyweights (BW) vertically and peak braking forces of 1.4 - 4.5 BW. The most recent studies (Hurrion et al., 2000; Portus et al., 2004) observed higher peak braking forces than those reported previously (3.54 and 4.5 BW, respectively). It has been suggested these higher peak forces may be due to a faster run-up speed, bowling technique, or the commitment and ease with which bowlers were able to bowl within the confines of the testing procedure (Hurrion et al., 2000).

The motion of the front leg during the front foot contact phase has been implicated as a mechanistic factor in the development of lower back injury in fast bowlers (Foster et al., 1989; Mason et al., 1989, as cited by Portus et al., 2004). Foster et al. (1989) recommended bowlers use a technique in which the front knee flexes during front foot contact, in order to dissipate ground reaction forces and reduce the likelihood of injury. This was supported in unpublished work by Hall (1999), in a study of eight English club fast and medium pace bowlers. Bowlers with a flexed front knee at the instant of front foot
contact experienced lower peak ground reaction forces than those with a straighter front knee (Elliott, 2000).

Similarly, Portus et al. (2004) observed that knee extension during the front foot contact phase was linked to higher peak braking forces. The use of an already extended / extending front knee was not only linked to increased peak ground reaction forces, these forces were also developed more rapidly. Significant moderate correlations were observed between the amount of knee extension during front foot contact and the time to peak vertical ($r = -0.41$, $p < 0.01$) and braking forces ($r = -0.41$, $p < 0.01$). The angle of the front knee at the instant of ball release was also observed to be significantly correlated with both vertical and braking peak ground reaction forces. Bowlers with a straighter front knee at ball release had higher peak ground reaction forces.

The aim of the current study was to identify relationships between the variation in ground reaction forces (peak forces and time to peak force) observed among elite fast bowlers and the motion of the front leg during the front foot contact phase of the bowling action.

### 7.3 METHODOLOGY

#### 7.3.1 PARTICIPANTS

Twenty elite male fast bowlers (mean ± standard deviation: age $20.1 \pm 2.6$ years; height $1.88 \pm 0.08$ m; body mass $81.5 \pm 7.1$ kg) took part in this investigation. Each bowler performed six maximum velocity deliveries which were recorded using an 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK) operating at 300 Hz. Ground reaction forces during the front foot contact phase of the bowling action were measured using a Kistler force plate ($900 \times 600$ mm, $1008$ Hz). This was built into the indoor testing facility and had a layer of artificial grass ($25$ mm) on its surface. The indoor cricket facility allowed bowlers to use a full length run-up on a standard sized artificial cricket pitch. All bowlers were identified as “fast bowlers” by England and Wales Cricket Board (ECB) fast bowling coaches and were deemed fit to bowl by their County Physiotherapist. The testing procedures were explained to each subject in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All subjects conducted a thorough warm-up prior to commencing data collection.
7.3.2 DATA COLLECTION

Forty-seven 14 mm retro-reflective markers were attached to each subject (Figure 7.1), positioned over bony landmarks in accordance with a full-body marker set developed specifically for the analysis of fast bowling techniques. An additional marker, in the form of a 15 x 15 mm patch of 3M Scotch-Lite reflective tape, was attached to the ball in order to enable the instant of ball release and the speed of the ball to be determined. Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990), enabling subject specific segmental inertia parameters to be determined for each bowler.

Figure 7.1 – The marker positions used in this study.

7.3.3 DATA PROCESSING

Three trials were selected for each bowler to be used in this study, identified as maximal velocity deliveries in which the bowlers hit the force plant cleanly during front foot contact with minimal marker loss. These trials were manually labelled and processed in Vicon’s Workstation and BodyBuilder software. The instants of back foot contact, front foot contact, front foot flat and ball release were identified using the tracked marker positions. Ground contact was defined to be the first frame in which the motion of the markers on the foot were observed to change due to contact with the ground. Front foot flat corresponded to the first frame in which the forefoot was on the ground. The instant of ball release was identified using the time-history of the distance between the marker on the ball and the mid-point of a pair of markers placed over the wrist. All marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz.
Joint centres were determined using a pair of markers placed across each joint, their midpoint corresponding to the joint centre. The “hip joint centring algorithm” of Davis et al. (1991) was used to identify the hip joint centres using markers placed over the left and right anterior superior iliac spine and the left and right posterior superior iliac spine. The motion of the back was tracked using the four markers on the pelvis in addition to markers placed over the proximal (sterna) and distal (clavicular) ends of the sternum as well as the spinous processes of L1, T10 and C7.

Three-dimensional local reference frames were defined describing an eighteen segment representation of the body (Figure 7.2). These consisted of: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two-segment foot. These local reference frames were defined using three markers on the segment itself, enabling segment orientations and joint angles to be calculated. The origins were located at the lower joint centre of the segment, when standing in an anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed to the subjects’ right (flexion-extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with the y-axis pointing down the wicket, the x-axis pointing to the right and the z-axis corresponding to the upwards vertical.

![Figure 7.2](image)

**Figure 7.2** – The eighteen local coordinate systems representing the full body.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) in order to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated
using an xyz sequence – representing an initial rotation about the x-axis of the parent, followed by rotation about a floating y-axis of the parent and finally the z-axis of the child. These rotations corresponded to flexion-extension, abduction-adduction or varus-valgus rotation, and longitudinal rotation, respectively.

7.3.4 DATA REDUCTION

Eight kinematic parameters were calculated for each trial, describing the run-up speed and front leg technique.

- run-up speed (horizontal)
- plant angle
- foot-strike indicator
- knee angle at front foot contact
- hip angle at front foot contact
- ankle flexion (front foot contact till ball release)
- knee flexion (front foot contact till ball release)
- hip flexion (front foot contact till ball release)

Angles describing the ankle (foot flat \( \approx 90^\circ \)), knee (straight = 180°) and hip (straight = 180°) on the front leg corresponded to the anatomical flexion / extension angle of the joint calculated using the 18-segment representation of a bowler. Joint flexion corresponded to a decrease in the joint angle; the amount of flexion was calculated for the ankle, knee and hip during the period from front foot contact until ball release. The extension of these joints typically occurred after the peak ground reaction force and as such was not included in this investigation.

In order to account for differences in the orientation of the foot at front foot contact, a “foot-strike indicator” was calculated for each trial, rather than using the ankle angle. This foot-strike indicator was the angle between the global y-axis (the line pointing down the wicket) and a line joining a projection of the ankle and MTP joint centres onto a vertical global plane (Figure 7.3A). A larger value of the “foot strike indicator” corresponds to a more dorsi-flexed foot orientation. Similarly, a “plant angle” was calculated by projecting the hip and ankle joint centres onto a vertical plane. The plant angle was the angle between the downwards vertical and a line joining these two projected points (Figure 7.3B). The horizontal run-up speed (global y-direction) was determined using the calculated
position of the centre of mass, from the 18-segment system. It was assumed the centre of mass moved with a constant horizontal velocity during a period of 18 frames (0.060 s) prior to the instant of back foot contact.

\[\text{(A)}\quad \text{(B)}\]

**Figure 7.3** – An illustration of the foot-strike indicator and plant angle.

Four kinetic parameters were also defined: peak forces in the vertical and horizontal directions (Figure 7.4); and the time from front foot contact until the occurrence of these peak forces. Peak forces were normalised using the bowlers’ body mass.

\[\text{Figure 7.4} \quad \text{A typical ground reaction force trace during the front foot contact phase, with the peak vertical (a) and peak braking (b) forces indicated.}\]
7.3.5 STATISTICAL ANALYSIS

All statistical analyses were performed within Statistical Package for the Social Sciences v.17 (SPSS Corporation, USA). The variation observed in each parameter (kinematic and kinetic) were assessed using an analysis of variance (ANOVA). The between-bowler variability (standard deviation of the observations) was compared with the standard deviation of the between-trial variability. This ranged from 8.79 – 20.74% (mean 12.82%) for the parameters calculated in this study, corresponding to an intra-class correlation coefficient of 0.96 – 0.99 (mean 0.98). As there was good between-trial repeatability for all technique parameters, the three trials analysed were averaged to provide representative data for each bowler. The effect of interactions between technique variables on each of the four kinetic variables were addressed separately using linear regression. A maximum of four variables were included in the predictive equation with the requirement for the inclusion of a variable being P < 0.10.

7.4 RESULTS

The twenty elite fast bowlers participating in this study released the ball at speeds of 32.80 - 39.72 m.s\(^{-1}\) (34.94 ± 1.67 m.s\(^{-1}\)). Using the front knee technique classification system introduced by Portus et al. (2004), the bowlers were classified as: 9 x flexor-extender; 6 x flexor; 3 x extender; and 2 x constant-brace. The mean peak vertical ground reaction force (6.72 ± 1.42 BW) and peak braking force (4.47 ± 0.75 BW) were within the range reported in previous studies. Details of the range, mean and standard deviation of each technique variable (Table 7.1) and each kinetic variable (Table 7.2) are provided below.
Table 7.1 – Details of the range, mean and standard deviation of each technique parameter for the group of bowlers.

<table>
<thead>
<tr>
<th>Technique Variable</th>
<th>Range</th>
<th>Mean ± Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-up speed (m.s⁻¹)</td>
<td>4.77 – 6.76</td>
<td>5.79 ± 0.58</td>
</tr>
<tr>
<td>Foot-strike indicator (°)</td>
<td>-30.8 – 11.0</td>
<td>-8.3 ± 13.2</td>
</tr>
<tr>
<td>Knee angle at front foot contact (°)</td>
<td>148.3 – 172.7</td>
<td>164.1 ± 6.1</td>
</tr>
<tr>
<td>Hip angle at front foot contact (°)</td>
<td>117.3 – 148.8</td>
<td>132.9 ± 9.3</td>
</tr>
<tr>
<td>Plant angle (°)</td>
<td>27.3 – 43.0</td>
<td>36.3 ± 3.9</td>
</tr>
<tr>
<td>Ankle flexion between front foot contact and ball release (°)</td>
<td>3.6 – 25.7</td>
<td>12.4 ± 6.3</td>
</tr>
<tr>
<td>Knee flexion between front foot contact and ball release (°)</td>
<td>0.0 – 44.8</td>
<td>16.6 ± 11.5</td>
</tr>
<tr>
<td>Hip flexion between front foot contact and ball release (°)</td>
<td>10.2 – 43.8</td>
<td>24.9 ± 9.7</td>
</tr>
</tbody>
</table>

Table 7.2 – Details of the range of values obtained for each kinetic parameter.

<table>
<thead>
<tr>
<th>Kinetic Variable</th>
<th>Range</th>
<th>Mean ± Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vertical force (BW)</td>
<td>3.99 – 8.63</td>
<td>6.72 ± 1.42</td>
</tr>
<tr>
<td>Peak braking force (BW)</td>
<td>2.55 – 6.05</td>
<td>4.47 ± 0.75</td>
</tr>
<tr>
<td>Time to peak vertical force (s)</td>
<td>0.009 – 0.050</td>
<td>0.030 ± 0.012</td>
</tr>
<tr>
<td>Time to peak braking force (s)</td>
<td>0.018 – 0.047</td>
<td>0.032 ± 0.009</td>
</tr>
</tbody>
</table>

The best individual predictor of peak vertical force was the foot-strike indicator (Table 7.3), explaining 30.0% of the variation observed. This was increased to 63.3% with the addition of plant angle and run-up speed into the predictive equation. Higher peak vertical ground reaction forces were associated with a more plantar-flexed foot at the instant of front foot contact, a smaller plant angle and a faster run-up speed.
Table 7.3 – Details of the best predictive equations produced for peak vertical force using linear regression.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Parameter(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Foot-strike indicator</td>
<td>-0.059</td>
<td>0.013</td>
<td>30.0</td>
</tr>
<tr>
<td>2</td>
<td>Foot-strike indicator</td>
<td>-0.052</td>
<td>0.022</td>
<td>41.2</td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.124</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Foot-strike indicator</td>
<td>-0.072</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.211</td>
<td>0.004</td>
<td>63.3</td>
</tr>
<tr>
<td></td>
<td>Run-up speed</td>
<td>1.416</td>
<td>0.007</td>
<td></td>
</tr>
</tbody>
</table>

There was no significant correlation between any individual technique parameter and the peak braking force; run-up speed was the parameter closest to being significant (P = 0.155) (Table 7.4). However, 31.4% of the variation in peak braking force was explained when run-up speed and the foot-strike indicator were entered into the predictive equation together. There was insufficient evidence to support the addition of any further technique parameters into the predictive equation. The relatively low percentage explained is perhaps attributable to the strong link between the peak braking force and the peak vertical force – on its own the peak vertical force explains 44.3% of the variation observed in the peak braking force.

Table 7.4 – The parameters that best explain the variation in peak braking force.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Parameter(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Run-up speed</td>
<td>0.428</td>
<td>0.155</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Run-up speed</td>
<td>0.691</td>
<td>0.027</td>
<td>31.4</td>
</tr>
<tr>
<td></td>
<td>Foot-strike indicator</td>
<td>-0.028</td>
<td>0.038</td>
<td></td>
</tr>
</tbody>
</table>

The variation in the time to peak force, for both the vertical and braking force, were best explained by the foot-strike indicator. The foot-strike indicator explained 44.9% and 63.2% of the variation in the time to peak vertical force and peak braking force, respectively (Tables 7.5 and 7.6). In both cases the percentage variation explained was increased (to 54.6% and 74.9% respectively) by the addition of the amount of knee flexion, between front foot contact and ball release, into the predictive equation. Those bowlers with the longest time until peak force were the most dorsi-flexed at front foot contact and had the least knee flexion.
Table 7.5 – Details of variables used to explain the time to peak vertical force.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Parameter(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Foot-strike indicator</td>
<td>0.001</td>
<td>0.001</td>
<td>44.9</td>
</tr>
<tr>
<td>2</td>
<td>Foot-strike indicator Knee flexion between front foot contact and ball release</td>
<td>0.001</td>
<td>0.000</td>
<td>54.6</td>
</tr>
</tbody>
</table>

Table 7.6 – Details of variables used to explain the time to peak braking force.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Parameter(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Foot-strike indicator</td>
<td>0.001</td>
<td>0.000</td>
<td>63.2</td>
</tr>
<tr>
<td>2</td>
<td>Foot-strike indicator Knee flexion between front foot contact and ball release</td>
<td>0.001</td>
<td>0.012</td>
<td>74.9</td>
</tr>
</tbody>
</table>

7.5 DISCUSSION

The results of this study indicate the variation in peak vertical force observed among the group of elite bowlers tested can be reasonably well explained (63% of the variation) using three parameters describing the front leg technique and the run-up. Those parameters being: the manner of foot-strike; plant angle; and run-up speed. Two of these parameters, run-up speed and the manner of foot-strike were also the best predictors of peak braking forces. The relatively low percentage of the variation explained for the peak braking force is due to the strong correlation between the peak forces in the vertical and braking directions ($r = 0.666, P = 0.001$).

The manner of foot-strike has not been considered previously in the literature, yet it was the best predictor of peak vertical force. A more plantar-flexed foot at the instant of front foot contact was observed to be linked to higher peak forces in both the vertical and braking directions. This suggests that by initially striking the ground with their heel at front foot contact, bowlers are able to cushion the impact. The bowlers who had the most extreme plantar-flexion at front foot contact were observed to have very little motion at the ankle during the initial part of the front foot contact phase. These bowlers typically locked their ankle in position throughout this phase and should be expected to experience a relatively undamped impact with the ground. Bowlers who were more dorsi-flexed (heel-
strikers) had far more ankle motion during this period as their foot ‘flapped down’ onto the floor. This motion of the foot could act as a means of cushioning the impact for the more dorsi-flexed bowlers.

A smaller plant angle at front foot contact was also linked to lower peak vertical ground reaction forces. This relationship should be expected as the resultant ground reaction force typically points approximately along the line of the front leg during the initial part of the front foot contact phase (Figure 7.5). By using a smaller plant angle, the vertical component of the ground reaction force is increased. This relationship between plant angle and peak vertical force is also likely to be partially dependent on the orientation of the thorax relative to the line of the front leg. If the front leg and thorax are aligned at front foot contact, as is more the case for bowlers with a smaller plant angle, the forces are likely to be transmitted up the length of the spine. Bowlers with a larger plant angle have their thorax less aligned with the front leg and the force is more likely to be partially absorbed by the muscles of the thorax.

(A)  (B)

Figure 7.5 – An illustration of the resultant ground reaction force during the initial part of the front foot contact phase for: (A) a bowler with a small plant angle; and (B) a bowler with a large plant angle.

A faster run-up speed was associated with higher peak forces in both the vertical and braking directions. Bowlers with a quicker run-up have more linear momentum as they strike the ground at front foot contact and would be expected to generate higher peak forces as the bowler rapidly slows the linear velocity of their centre of mass. These results
support the suggestion of Hurrion et al. (2000) that faster run-up speeds may be partly attributable to the higher peak braking forces reported in recent studies.

Previous researchers have calculated loading rates during the front foot contact phase. These have been defined as the mean rate of force development from the instant of front foot contact until peak force occurred (e.g. Hurrion et al., 2000). However, these loading rates are heavily dependent on the magnitude of the peak force. It was therefore decided that the time to peak force would be considered in the current study, enabling those aspects of technique which account for the delay in the occurrence of the peak force to be identified.

The best individual predictor of the time to peak force, in both the vertical and braking directions, was the foot-strike indicator. Those bowlers who were more dorsi-flexed at front foot contact took a longer time to reach their peak force. Visual inspection of the data collected suggested that the majority of bowlers recorded their peak ground reaction forces a few frames after their forefoot made contact with the ground. Consequently, the additional time taken for the more dorsi-flexed bowlers to reach peak force can be considered to be approximately the delay between the instant of front foot contact and the forefoot hitting the ground.

The amount of knee flexion was also observed to be a significant explanatory variable for the time to peak forces, with increased knee flexion being associated with a shorter time to peak force. These results appear to directly contradict those of Portus et al. (2004) who reported that bowlers who used a technique in which the front knee extends, or was already extended, had a shorter time to peak force. When considering these results it is important to remember that in both these studies the knee flexion or extension was calculated over the entire period from front foot contact until ball release. The peak ground reaction force, however, occurs very early within this period.

In the current study, nine of the bowlers tested were classified as having a flexor-extender front knee technique, meaning they had at least 10° of flexion prior to 10° or more extension. As such, it was decided not to calculate the amount of knee extension as it was deemed not to have a mechanical link to the peak forces recorded. When the knee angles for the bowlers tested in the current study were examined in more detail, it was observed that the majority of bowlers were actually extending during the first few frames of the front foot contact phase. As the ground reaction force increased, most of these bowlers went
into knee flexion. These results suggest that the bowlers were attempting to keep their leg extended throughout the front foot contact phase, however, many were unable to withstand the forces exerted by the ground and flexed their front knee as a result. In this light, the knee flexion observed in bowlers is as a consequence of the shorter time to peak force, as opposed to the action of the knee determining the delay as has been proposed in previous studies.

7.6 CONCLUSIONS

The results of this study suggest that the variation in peak force and time to peak force during the front foot contact phase of the fast bowling action can be explained using variables describing the initial orientation of the front leg at the instant of front foot contact. In contrast to suggestions in previous studies, it would appear the flexion of the front knee, during the front foot contact phase, occurring in the majority of bowlers is as a consequence of the high peak ground reaction forces. To understand the mechanics of these relationships in more detail, future studies should investigate the effect of changes to front leg technique on the ground reaction forces for individual bowlers.
DOES ‘OPTIMAL’ PERFORMANCE NECESSITATE HIGHER GROUND REACTION FORCES? A FAST BOWLING PERSPECTIVE

8.1 ABSTRACT

Within many sporting activities, techniques which are ‘optimal’ in terms of performance require larger forces and loading rates to be exerted on the body, potentially increasing the likelihood of injury (e.g. maximum velocity sprinting, drop jumping). Previous research has suggested this is true in cricket, with bowlers who release the ball at the fastest speeds having the highest peak ground reaction forces and loading rates. Twenty elite male fast bowlers performed three maximum velocity deliveries of good length in an indoor cricket facility. Kinematic data were collected using an 18 camera Vicon Motion Analysis System operating at 300 Hz. Ground reaction forces during the front foot contact phase of the bowling action were measured using a Kistler force plate (1008 Hz). Ball release speed and the instant of ball release were calculated using a marker placed on the ball. Correlations between parameters were assessed using Pearson’s correlation coefficients. Rather than being linked to higher forces and loading rates, ball speed was positively correlated with the total horizontal impulse between front foot contact and ball release. Ball release speed was also positively correlated with run-up speed and the plant angle at front foot contact. In contrast to previous reported relationships, faster bowlers were observed to have a lower ball release height. The findings of this investigation contradict previous suggestions of a trade-off between ‘optimal’ performance (maximum ball release speed) and the forces exerted on the body (peak ground reaction forces and loading rates). The perhaps counterintuitive relationship between ball release height and ball speed emphasises the need to understand the underlying mechanics of a technique before intuitive judgments are made. This study motivates further investigation of the generation of ball pace by fast bowlers, enabling the mechanics of the observed links between technique and ball speed to be understood in more detail.
8.2 INTRODUCTION

Within many sporting activities, techniques which are ‘optimal’ in terms of performance cause larger forces and loading rates to be exerted on the body, potentially increasing the likelihood of injury e.g. maximum velocity sprinting (Weyand et al., 2000) and drop jumping. It is believed there is a similar trade off for fast bowling in cricket, with bowlers who release the ball at faster speeds experiencing higher peak ground reaction forces and loading rates (Portus et al., 2004).

Fast bowlers have the highest injury prevalence in professional cricket (Newman, 2003; Orchard et al., 2006), the most common cause of lost playing time being lumbar stress fractures or other lumbar injury (Newman, 2003). These injuries occur predominantly on the opposite side to the bowling arm (non-dominant side) (Gregory et al., 2004; Ranson et al., 2005). Previous researchers have suggested large peak ground reaction forces during the early part of the front foot contact phase could be a major cause of lower back injuries in fast bowlers (Bartlett et al., 1996; Ranson et al., 2008). These high peak forces coincide with lower trunk movements known to produce high contralateral facet joint contact forces (lower trunk extension, contralateral side-flexion and ipsilateral rotation). A fundamental issue to address, therefore, is whether these high peak forces are unavoidable if a bowler is to release the ball at high speeds.

Few researchers have addressed this issue directly. Portus et al. (2004) tested a group of 42 high performance male fast bowlers and observed that faster bowlers had both higher peak forces and loading rates than slower bowlers. It has been suggested that bowlers should use a ‘flexor-extender’ technique during the front foot contact phase. Initially flexing their front knee in order to dissipate ground reaction forces, then extending in order to maximise ball release speeds (Bartlett et al., 1996). The aim of the current study was to investigate the relationship between ball release speed and ground reaction forces, specifically to address whether high peak forces and loading rates are necessary in order to bowl quickly.
8.3 METHODOLOGY

8.3.1 PARTICIPANTS

Twenty elite male fast bowlers (mean ± standard deviation: age 20.1 ± 2.6 years; height 1.88 ± 0.08 m; body mass 81.5 ± 7.1 kg) performed six maximum velocity deliveries of good length, using their full length run-up, in an indoor practice facility. All bowlers were identified as “fast bowlers” by England and Wales Cricket Board (ECB) fast bowling coaches and were deemed fit to bowl by their County Physiotherapist. Kinematic data were collected using an 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK) operating at 300 Hz. Ground reaction forces were measured using a Kistler force plate (900 x 600 mm, 1008 Hz) during the front foot contact phase of the bowling action. The force plate was built into the indoor testing facility and had a layer of artificial grass (25 mm) on its surface. The testing procedures were explained to each subject in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All subjects conducted a thorough warm-up prior to commencing data collection.

8.3.2 DATA COLLECTION

Forty-seven 14 mm retro-reflective markers were attached to each subject, positioned over bony landmarks in accordance with a full-body marker set developed specifically for the analysis of fast bowlers’ techniques (Figure 8.1). An additional marker, in the form of a 15 x 15 mm patch of 3M Scotch-Lite reflective tape, was attached to the ball in order to enable the instant of ball release and the speed of the ball to be determined. Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990), enabling subject specific segmental inertia parameters to be determined for each bowler.
8.3.3 DATA PROCESSING

Three trials were selected for each bowler to be used in this study, identified as maximal velocity deliveries with minimal marker loss. These trials were manually labelled and processed in Vicon’s Workstation and BodyBuilder software. The instants of back foot contact, front foot contact, front foot flat and ball release were identified using the tracked marker positions. Ground contact was defined to be the first frame in which the motion of the markers on the foot were observed to change due to contact with the ground. Front foot flat corresponded to the first frame in which the forefoot was on the ground. Ball release was identified using the time history of the distance between the marker on the ball and the mid-point of a pair of markers placed over the wrist. All marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz.

Joint centres were determined using a pair of markers place across each joint, their mid-point corresponding to the joint centre. The “hip joint centring algorithm” of Davis et al. (1991) was used to identify the hip joint centres using markers placed over the left and right anterior superior iliac spine and the left and right posterior superior iliac spine. The motions back were tracked using the four markers on the pelvis in addition to markers placed over the proximal (sterna) and distal (clavicular) ends of the sternum as well as the spinous processes of L1, T10 and C7.

Figure 8.1 –The marker positions used in this study.
Local reference frames describing a three-dimensional eighteen segment full-body representation of a bowler were defined. These consisted of: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two-segment foot. These local reference frames were defined using three markers on the segment itself, enabling segment orientations and joint angles to be calculated. The origins were located at the lower joint centre of the segment, when standing in an anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed to the subjects’ right (flexion-extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with the y-axis pointing down the wicket, the x-axis pointing to the right and the z-axis representing the upwards vertical.

8.3.4 DATA REDUCTION

Six kinetic parameters were calculated for each trial: peak forces in the vertical and horizontal (braking) directions; the peak loading rate in both the vertical and braking directions; and the vertical and braking impulse between front foot contact and ball release. Peak forces, loading rates and impulses were all normalised using the bowlers’ body mass. Loading rates were calculated as defined by Hurrion et al. (2000) – the average rate of loading up to the peak force. A typical force trace during the front foot contact, with the instant of peak vertical and braking forces indicated is illustrated in Figure 8.2.

![Figure 8.2](image.png)

Figure 8.2 – A typical ground reaction force trace during front foot contact, with the peak vertical (a) and peak braking (b) forces indicated.
Four kinematic parameters were also calculated for each trial, these parameters described ball release speed, the horizontal run-up speed (just prior to back foot contact), the orientation of the front lower limb at the instant of front foot contact and the ball release height.

The horizontal run-up speed (in the global y-direction) was determined using the calculated position of the centre of mass, from the 18-segment representation of the bowler. It was assumed the centre of mass moved with a constant horizontal velocity during the period of 18 frames (0.060 s) prior to the instant of back foot contact. Ball release speed was determined in a similar manner, using the motion of the marker on the ball during a period of 10 frames (0.033 s) from the instant of ball release. A constant velocity was assumed in the global x and y-directions, constant acceleration equations were used to calculate the vertical velocity at ball release.

The front leg orientation was described using a two-dimensional plant angle, representing the angle between the downwards vertical and a straight line joining the front hip and ankle joint centres (Figure 8.3). Ball release heights were normalised based on the bowler’s standing height.

![Image of bowler with plant angle highlighted]

**Figure 8.3** – An illustration of the calculated plant angle.

### 8.3.5 STATISTICAL ANALYSIS

All statistical analysis was performed within Statistical Package for the Social Sciences v.17 (SPSS Corporation, USA). The variation observed in each parameter (kinematic and
kinetic) were assessed using an analysis of variance (ANOVA). The between-bowler variability (standard deviation of the observations) was compared with the standard deviation of the between-trial variability. This ranged from 3.63 – 23.19% (mean 12.82%) for the parameters calculated in this study, corresponding to an intra-class correlation coefficient of 0.95 – 1.00 (mean 0.98). As there was good between-trial repeatability for all technique parameters, the three trials analysed were averaged to provide representative data for each bowler. Correlations were assessed using a two-tailed Pearson’s product moment coefficient and were deemed to be significant for \( P < 0.10 \).

8.4 RESULTS

The twenty elite fast bowlers tested as part of this investigation had a mean run-up speed of 5.79 m.s\(^{-1}\) and released the ball at 34.94 m.s\(^{-1}\). The mean peak vertical ground reaction force (6.72 ± 1.42 BW) and peak braking force (4.47 ± 0.75 BW) were within the range of values reported in previous studies. Using the front knee technique classification system introduced by Portus et al. (2004), the bowlers were classified as: 9 x flexor-extender; 6 x flexor; 3 x extender; and 2 x constant-brace. Details of the range, mean and standard deviation of each kinetic variable (Table 8.1) and each kinematic variable (Table 8.2) are provided below.

**Table 8.1 – Details of the range of values obtained for each kinetic parameter.**

<table>
<thead>
<tr>
<th>Kinetic Variable</th>
<th>Range</th>
<th>Mean ± Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vertical force (BW)</td>
<td>3.99 – 8.63</td>
<td>6.72 ± 1.42</td>
</tr>
<tr>
<td>Peak braking force (BW)</td>
<td>2.55 – 6.05</td>
<td>4.47 ± 0.75</td>
</tr>
<tr>
<td>Peak vertical loading rate (BW.s(^{-1}))</td>
<td>85.74 – 892.44</td>
<td>309.47 ± 219.49</td>
</tr>
<tr>
<td>Peak horizontal loading rate (BW.s(^{-1}))</td>
<td>55.16 – 282.12</td>
<td>153.88 ± 55.63</td>
</tr>
<tr>
<td>Vertical impulse (BW.s)</td>
<td>0.205 – 0.320</td>
<td>0.277 ± 0.029</td>
</tr>
<tr>
<td>Braking impulse (BW.s)</td>
<td>0.207 – 0.088</td>
<td>0.155 ± 0.034</td>
</tr>
</tbody>
</table>
Table 8.2 – Details of the range, mean and standard deviation of each kinematic parameter calculated for the group of bowlers.

<table>
<thead>
<tr>
<th>Technique Variable</th>
<th>Range</th>
<th>Mean ± Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball release speed (m.s(^{-1}))</td>
<td>32.80 – 39.72</td>
<td>34.94 ± 1.67</td>
</tr>
<tr>
<td>Run-up speed (m.s(^{-1}))</td>
<td>4.77 – 6.76</td>
<td>5.79 ± 0.58</td>
</tr>
<tr>
<td>Plant angle (°)</td>
<td>27.3 – 43.0</td>
<td>36.3 ± 3.9</td>
</tr>
<tr>
<td>Ball release height (%)</td>
<td>105.4 – 121.6</td>
<td>112.8 ± 4.1</td>
</tr>
</tbody>
</table>

Details of the correlations observed between ground reaction force characteristics and ball release speed are provided in Table 8.3. In contrast to previous investigations, an almost significant correlation was observed between ball release speed and lower peak vertical ground reaction force \((r = -0.364, P = 0.114)\), with faster bowlers experiencing the lowest forces. Similarly, the results of the current study indicate the fastest bowlers actually had the lowest loading rates both vertically \((r = -0.452, P = 0.046)\) and horizontally \((r = -0.484, P = 0.031)\). Rather than higher peak forces and loading rates, it was a larger horizontal impulse, in the period from front foot contact until ball release, which characterised the fastest bowlers \((r = 0.574, P = 0.008)\).

Table 8.3 – Correlations between kinetic parameters and ball release speed \((r, P)\).

<table>
<thead>
<tr>
<th>Kinetic Parameters</th>
<th>Ball Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vertical force</td>
<td>-0.364, 0.114</td>
</tr>
<tr>
<td>Peak braking force</td>
<td>0.078, 0.745</td>
</tr>
<tr>
<td>Peak vertical loading rate</td>
<td>-0.452, 0.046</td>
</tr>
<tr>
<td>Peak horizontal loading rate</td>
<td>-0.484, 0.031</td>
</tr>
<tr>
<td>Vertical impulse</td>
<td>0.234, 0.322</td>
</tr>
<tr>
<td>Braking impulse</td>
<td>0.574, 0.008</td>
</tr>
</tbody>
</table>

Significant correlations were observed between ball release speed and all three technique parameters: run-up speed; front leg plant angle; and normalised ball release height (Table 8.4). A quicker run-up and a larger plant angle (leg extended further out in front) were both linked to increased ball release speed \((r = 0.499, P = 0.025\) and \(r = 0.522, P = 0.018\), respectively). Interestingly a lower ball release height was linked to faster ball release.
speeds ($r = -0.599, P = 0.005$). Relationships between these technique parameters and the braking impulse were also considered (Table 8.4). Both a larger plant angle and a lower ball release height were significantly correlated with a larger braking impulse ($r = 0.706, P = 0.001$ and $r = -0.570, P = 0.009$, respectively). An almost significant correlation was observed between faster run-up speeds and an increased braking impulse ($r = 0.363, P = 0.115$).

**Table 8.4** – Correlations between ball release speed, braking impulse and parameters describing the kinematics of bowling technique ($r, P$).

<table>
<thead>
<tr>
<th></th>
<th>Run-up Speed</th>
<th>Plant Angle</th>
<th>Ball Release Height</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ball Speed</strong></td>
<td>0.499, 0.025</td>
<td>0.522, 0.018</td>
<td>-0.599, 0.005</td>
</tr>
<tr>
<td><strong>Braking impulse</strong></td>
<td>0.363, 0.115</td>
<td>0.706, 0.001</td>
<td>-0.570, 0.009</td>
</tr>
</tbody>
</table>

**8.5 DISCUSSION**

An ‘ideal’ fast bowling technique enables the bowler to release the ball as quickly as possible, whilst retaining accuracy, without predisposing them to injury. It is currently believed there is a trade-off between ball release speed and ground reaction forces, with the fastest bowlers experiencing the highest peak forces and loading rates (Portus et al., 2004). The results of the current study strongly contradict these beliefs; significant correlations were found between ball release speed and peak loading rates both vertically and horizontally. There was also evidence of a negative correlation between ball release speed and peak vertical force, however, this was not significant in the sample of bowlers tested ($P = 0.114$). Instead, these results suggest it is actually a large braking impulse, between front foot contact and ball release, which is required for fast ball release speeds to be achieved.

Faster ball release speeds were linked to a quicker run-up and a larger plant angle at front foot contact; these results give an indication of the mechanics underlying the fast bowling action. A faster run-up generates more linear momentum. As a bowler plants their front leg this linear momentum is converted into angular momentum about the front foot; a quicker angular velocity (for a particular release height) will produce a faster linear velocity of the hand and ball at release. The correlation between plant angle and release...
speed suggests that by adopting a large plant angle at front foot contact, bowlers are able to convert more of the momentum generated during their run-up into ball speed.

This mechanism is further supported by the observed link between plant angle and braking impulse; bowlers with a larger plant angle are able to generate a larger impulse. The resultant ground reaction force is typically directed along the longitudinal axis of the leg during the front foot contact phase. By adopting a larger plant angle at front foot contact, the horizontal component of the ground reaction force is increased whilst the vertical component decreases. Furthermore, the knee is able to withstand greater forces without flexing if the force is applied along its length than if applied tangentially. By using a larger plant angle the braking force becomes more aligned with the line of the leg and unsurprisingly the bowlers are able to generate a larger braking impulse.

The observed relationship between a lower normalised ball release height and faster delivery speeds contradicts proposed relationships in the literature and is not so easily explained mechanically. This would appear to be counterintuitive, as increasing the distance of the ball from its centre of rotation should increase its linear speed. Therefore, the correlation between ball release height and ball speed is likely to be as a consequence of other aspects of the bowling action, such as the larger plant angle and increased trunk flexion observed in faster bowlers (Chapter 6), rather than representing a direct link.

Crucially, the results of this investigation suggest the use of a large plant angle at front foot contact enables bowlers to generate a large braking impulse, whilst decreasing the peak vertical ground reaction force. Hence, the quickest bowlers do not require the highest ground reaction forces.

### 8.6 CONCLUSIONS

This investigation indicates that ball release speed in fast bowling is dependent on the horizontal impulse generated at the ground, between front foot contact and ball release, not peak forces and loading rates as has been suggested previously. These findings contradict the suggestion of a trade-off between ‘optimal’ performance (maximum ball release speed) and the forces exerted on the body (peak ground reaction forces and loading rates). The perhaps counterintuitive relationship between ball release height and ball speed emphasises the need to understand the underlying mechanics of a technique before intuitive judgments
should be made. This study motivates further investigation of the generation of ball pace by fast bowlers, enabling the mechanics of the observed links between technique and ball speed to be understood in more detail.
9.1 ABSTRACT

It has been proposed that large peak ground reaction forces during the front foot contact phase of the fast bowling action, together with lateral flexion, hyperextension and rotation of the lower back, are a major cause of lower back injuries in fast bowlers. The aim of this study was to assess the relationships between the peak forces in the lower back, the peak ground reaction forces and the motion of the front leg during the front foot contact phase.

Data were collected for a group of twenty elite fast bowlers, each performing six maximal velocity deliveries of good length in an indoor practice facility. Three dimensional kinematic data in additional to kinetic data for the front foot contact phase of the fast bowling action were captured using an 18 camera Vicon Motion Analysis System (300 Hz). Forty-seven retro-reflective markers were attached to each subject, an additional marker was attached to the ball to enable ball release speed and the instant of ball release to be determined. All marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz. Eight kinematic parameters were determined for each trial, describing the run-up speed and front leg technique. Two kinetic parameters were also determined, the peak resultant ground reaction force and the peak force in the lower back. A representative value for each parameter was calculated for each subject – the mean value from the best three trials performed. The effect of the technique variables and peak ground reaction force on the peak force in the lower back were addressed using linear regression. The results indicate peak forces in the lower back are determined predominantly by the magnitude of the ground reaction forces. It also appears that peak forces in the lower back are predominantly determined by the bowlers’ initial conditions at the instant of front foot contact (e.g. the manner of foot-strike, the plant angle at front foot contact and the run-up speed), rather than their technique during the front foot contact phase. Future work should look to address the likelihood of lower back injuries in fast bowlers by considering the peak forces in the back as well as the orientation of the spine during this period of the action.
9.2 INTRODUCTION

Fast bowlers have the highest injury prevalence in professional cricket (Newman, 2003; Orchard et al., 2002; Stretch, 2003), the most common injuries being lumbar stress fractures and lumbar injury on the non-dominant side (Newman, 2003). Injury rates among fast bowlers are similar to those reported for contact sports such as Australian rules football and the Rugby football codes (Orchard et al., 2006). These high injury rates have prompted a number of previous studies to address the potential causes of lower back injuries in fast bowlers.

It is generally accepted that lower back stress fractures are common in sports requiring repeated episodes of combined trunk rotation and hyperextension (Brukner and Khan, 1997; as cited by Portus et al., 2004). Chosa et al. (2004) found unilateral pars interarticularis stress to be greatest under combinations of compression with lumbar extension, compression with lumbar side flexion to the same side and compression with lumbar rotation to the opposite side.

Ferdinands et al. (2009) developed a fifteen segment three-dimensional inverse-dynamics model of a fast bowler and used this to investigate and identify the magnitude and temporal characteristics of the lumbar spine kinetics during the bowling action. They observed that the lumbar spine segment was subjected to very high loading during the bowling action, particularly during the front foot contact phase. Three-dimensional studies have confirmed that lower trunk movements known to produce high contralateral facet joint forces typically peak just after the instant of front foot contact (Burnett et al., 1998; Ranson et al., 2008).

When bowling, the ground reaction forces generated during front foot contact phase are transmitted via the bones, tendons and muscles to the knee and hip joints and absorbed by the body (Nigg, 1992). If the spine is erect, the intervertebral compressive forces developed during front foot contact are more likely to be resisted by the bowler’s intervertebral discs. However, in a lordotic posture or when the spine is hyper-extended, the facet joints may bear more of this compressive force (Foster et al., 1989).

The role of the front lower limb (leg) has been implicated as a mechanistic factor in the development of lower back injury (Foster et al., 1989; Mason et al., 1989, as cited by Portus et al., 2004). The use of a technique in which the knee flexes during the front foot
contact phase was recommended by Foster et al. (1989), in order to dissipate ground reaction forces and reduce the likelihood of injury. This claim was supported in unpublished work by Hall (1999) in a study of eight English club fast and medium bowlers. Bowlers who landed with a flexed knee joint experienced a lower ground reaction force at front foot impact than those who landed with a straighter front leg (as cited by Elliott, 2000).

As yet, no studies have calculated the internal forces experienced in the lower back of bowlers during this period of the front foot contact phase when lower back injuries are believed to be caused. The current study aims to address this issue, using inverse dynamics to assess relationships between the motion of the front leg during the front foot contact phase and the forces within the lower back.

9.3 METHODOLOGY

9.3.1 PARTICIPANTS

Twenty elite fast bowlers (mean ± standard deviation: age 20.1 ± 2.6 years; height 1.88 ± 0.08 m; body mass 81.5 ± 7.1 kg) participated in this study. All bowlers performed six maximum velocity deliveries of good length, recorded using an 18 camera Vicon Motion Analysis System operating at 300 Hz (OMG Plc., Oxford, UK). Synchronous ground reaction forces during the front foot contact phase of the bowling action were recorded within the Vicon software by means of a Kistler force plate (900 x 600 mm, 300 Hz). Data were collected in an indoor cricket facility, allowing bowlers to use their full length run-up on a standard sized artificial cricket pitch. The force plate was built into the testing facility and had a thin covering (25 mm) of artificial grass affixed to its surface. All bowlers were identified as “fast bowlers” by England and Wales Cricket Board (ECB) fast bowling coaches and were deemed fit to bowl by their County Physiotherapist. The testing procedures were explained to each subject in accordance with Loughborough University ethical guidelines and an informed consent form signed. All subjects performed a thorough warm-up prior to commencing data collection.
9.3.2 DATA COLLECTION

Forty-seven 14 mm retro-reflective markers were attached to each subject (Figure 9.1), positioned over bony landmarks in accordance with a marker set developed specifically for the analysis of fast bowling technique. An additional marker, in the form of a 15 x 15 mm patch of 3M Scotch-Lite reflective tape, was attached to the ball enabling the instant of ball release and the ball release speed to be determined. Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990), enabling subject-specific segmental parameters to be determined for each bowler.

Figure 9.1 – The marker positions used in this study.

9.3.3 DATA PROCESSING

The best three bowling trials, maximum velocity deliveries with minimal marker loss, were selected for each bowler. These trials were manually labelled and processed using the Vicon Workstation and BodyBuilder software (OMG Plc., Oxford, UK). The instants of front foot contact, front foot flat and ball release were identified for each trial, using the motion of the markers on the front foot. The instant of ground contact was defined as the first frame in which the motion of the foot was observed to change due to contact with the ground. Front foot flat corresponded to the first frame in which the forefoot was on the ground – for forefoot strikers, front foot contact and front foot flat were the same instant. The instant of ball release was identified using the time-history of the distance between the marker on the ball and the mid-point of a pair of markers positioned over the wrist. All
marker trajectories were filtered using a fourth-order low pass Butterworth filter (double pass) with a cut-off frequency of 30 Hz.

Joint centres were defined using a pair of markers placed across each joint, positioned such that their mid-point corresponded to the joint centre. The hip joint centres were calculated using the “hip joint centring algorithm” (Davis et al., 1991) from markers placed over the left and right anterior superior iliac spine (LASI and RASI) and the left and right posterior superior iliac spine (LPSI and RPSI). Lower and upper back motions were tracked using the four markers on the pelvis in addition to markers placed over the proximal (sterna) and distal (clavicular) ends of the sternum (STRN and CLAV) as well as the spinous processes of L1, T10 and C7. Joint centres for the lower back (LOWJC), upper back (MIDJC) and the head and neck segment (TOPJC) were defined using the methodology of Roosen (2007). These three joint centres were defined as:

\[
\text{LOWJC} = \text{SACR} + 0.2 \times (\text{PELF} - \text{SACR}) \\
\text{where,} \\
\text{SACR} = (\text{RPSI} + \text{LPSI}) / 2 \\
\text{PELF} = (\text{RASI} + \text{LASI}) / 2 \\
\text{MIDJC} = \text{T10} + 0.125 \times (\text{FThorax} - \text{BThorax}) \\
\text{where,} \\
\text{FThorax} = (\text{CLAV} + \text{STRN}) / 2 \\
\text{BThorax} = (\text{C7} + \text{T10}) / 2 \\
\text{TOPJC} = \text{C7} + 0.125 \times (\text{C7} - \text{CLAV}).
\]

Local reference frames were defined comprising a full-body representation of the bowler, consisting of: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two-segment foot. A three-dimensional local coordinate system was defined for each segment (Figure 9.2), using three markers on the segment itself. This enabled segment orientations and joint angles to be calculated. The segment origin was located at the lower joint centre of the segment when a bowler was standing in the anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the subject’s right (flexion-extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with
the y-axis pointing down the wicket, the x-axis pointing to the right and the z-axis corresponding to the upwards vertical.

**Figure 9.2** – The eighteen local coordinate systems representing the full body.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using an xyz sequence – representing an initial rotation about the x-axis of the parent, followed by rotation about a floating y-axis of the parent and finally the z-axis of the child. These rotations corresponded to flexion-extension, abduction-adduction or varus-valgus rotation, and longitudinal rotation, respectively.

In order to perform inverse dynamics analysis in Vicon’s Bodybuilder software, a kinetic hierarchy was defined (Figure 9.3). The connection points between segments were defined as the respective joint centres (all joints were pin joints), and segmental parameters were obtained from the geometric model of Yeadon (1990). This enabled the forces applied to the bottom the lower back segment to be calculated in the local reference frame of the pelvis segment.
9.3.4 DATA REDUCTION

Eight kinematic parameters were calculated for each trial, describing the run-up speed and front leg technique:

- run-up speed (horizontal)
- plant angle
- foot-strike indicator
- knee angle at front foot contact
- hip angle at front foot contact
- ankle flexion (front foot contact till ball release)
- knee flexion (front foot contact till ball release)
- hip flexion (front foot contact till ball release)
Angles describing the ankle (foot flat ≈ 90°), knee (straight = 180°) and hip (straight = 180°) of the front leg corresponded to the anatomical flexion / extension angle of the joint calculated using the 18-segment representation of a bowler. Joint flexion corresponded to a decrease in the joint angle; the amount of flexion was calculated for the ankle, knee and hip during the period from front foot contact until ball release.

In order to account for differences in the orientation of the foot at front foot contact, a “foot-strike indicator” was calculated for each trial, rather than using the ankle angle. This foot-strike indicator was the angle between the global y-axis and a line joining a projection of the ankle and MTP joint centres onto a vertical global plane (Figure 9.4A). Similarly, a “plant angle” was calculated by projecting the hip and ankle joint centres onto a vertical plane. The plant angle was the angle between the downwards vertical and a line joining these two projected points (Figure 9.4B). The horizontal run-up speed (global y-direction) was determined using the calculated position of the centre of mass, from the 18-segment representation. It was assumed the centre of mass moved with a constant horizontal velocity during a period of 18 frames (0.060 s) prior to the instant of back foot contact.

![Figure 9.4](image)

Figure 9.4 – An illustration of: (A) the foot-strike indicator; and (B) the plant angle.

Two kinetic parameters were also calculated from the inverse dynamics analysis (Figure 9.5). These were: peak resultant ground reaction force; and the peak resultant force at the base of the lumbar spine. These peak forces were normalised using the bowlers’ body mass.
Figure 9.5 – An illustration of the peak resultant forces at the ground and those calculated in the lower back using inverse dynamics.

9.3.5 STATISTICAL ANALYSIS

All statistical analysis was performed within Statistical Package for the Social Sciences v.17 (SPSS Corporation, USA). The variation observed in each parameter (kinematic and kinetic) were assessed using an analysis of variance (ANOVA). The between-bowler variability (standard deviation of the observations) was compared with the standard deviation of the between-trial variability. This ranged from 8.79 – 20.74% (mean 13.06%) for the parameters calculated in this study, corresponding to an intra-class correlation coefficient of 0.96 – 0.99 (mean 0.98). As there was good between-trial repeatability for all parameters, the three trials analysed were averaged to provide representative data for each bowler. The effect of interactions between technique variables and the peak resultant ground reaction force on the peak forces in the lower back were addressed using linear regression. A maximum of four variables were included in the predictive equation with the requirement for the inclusion of a variable being P < 0.10.
9.4 RESULTS

The twenty elite fast bowlers participating in this study released the ball at speeds of 32.80 - 39.72 m.s\(^{-1}\) (mean 34.94 ± 1.67 m.s\(^{-1}\)). Using the front knee technique classification system introduced by Portus et al. (2004), the bowlers were classified as: 9 x flexor-extender; 6 x flexor; 3 x extender; and 2 x constant-brace. The peak resultant ground reaction force during the front foot contact phase ranged from 4.89 – 9.85 BW and the calculated peak resultant force in the lower back was 2.82 – 7.51 BW. Details of the values obtained for each parameter for the group of bowlers tested in this study are provided in Table 9.1.

The best individual predictor of the peak resultant force in the lower back was the peak resultant force at the ground, explaining 93.9% of the variation observed (Table 9.2). Minor improvements to the predictive equation were made by the addition of: plant angle; the amount of hip flexion between front foot contact and ball release; and the front knee angle at front foot contact. Although the addition of these three extra parameters only improved the explained variation in peak resultant lower back force to 97.8%, there was significant evidence (P < 0.1) for the inclusion of each of these parameters.

**Table 9.1** – Details of the range, mean and standard deviation for each calculated parameter.

<table>
<thead>
<tr>
<th>Technique Parameter</th>
<th>Range</th>
<th>Mean ± Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-up speed (m.s(^{-1}))</td>
<td>4.77 – 6.76</td>
<td>5.79 ± 0.58</td>
</tr>
<tr>
<td>Peak resultant ground reaction force (BW)</td>
<td>4.89 – 9.85</td>
<td>7.81 ± 1.37</td>
</tr>
<tr>
<td>Peak resultant lower back force (BW)</td>
<td>2.82 – 7.51</td>
<td>5.41 ± 1.35</td>
</tr>
<tr>
<td>Heel-strike indicator (°)</td>
<td>-30.8 – 11.0</td>
<td>-8.3 ± 13.2</td>
</tr>
<tr>
<td>Knee angle at front foot contact (°)</td>
<td>148.3 – 172.7</td>
<td>164.1 ± 6.1</td>
</tr>
<tr>
<td>Hip angle at front foot contact (°)</td>
<td>117.3 – 148.8</td>
<td>132.9 ± 9.3</td>
</tr>
<tr>
<td>Plant angle (°)</td>
<td>27.3 – 43.0</td>
<td>36.3 ± 3.9</td>
</tr>
<tr>
<td>Ankle flexion from front foot contact till ball release (°)</td>
<td>3.6 – 25.7</td>
<td>12.4 ± 6.3</td>
</tr>
<tr>
<td>Knee flexion from front foot contact till ball release (°)</td>
<td>0.0 – 44.8</td>
<td>16.6 ± 11.5</td>
</tr>
<tr>
<td>Hip flexion from front foot contact till ball release (°)</td>
<td>10.2 – 43.8</td>
<td>24.9 ± 9.7</td>
</tr>
</tbody>
</table>
Table 9.2 – Details of the predictive equations obtained explaining the variation in peak resultant lower back force when the peak resultant ground reaction force (GRF) was used as an input parameter.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Variable(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peak resultant GRF</td>
<td>0.950</td>
<td>0.000</td>
<td>93.9</td>
</tr>
<tr>
<td>2</td>
<td>Peak resultant GRF</td>
<td>0.904</td>
<td>0.000</td>
<td>96.3</td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.056</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Peak resultant GRF</td>
<td>0.933</td>
<td>0.000</td>
<td>97.2</td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.054</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hip flexion from front foot contact till ball release</td>
<td>0.014</td>
<td>0.031</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Peak resultant GRF</td>
<td>0.945</td>
<td>0.000</td>
<td>97.8</td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.065</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hip flexion</td>
<td>0.016</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knee angle at front foot contact</td>
<td>-0.019</td>
<td>0.066</td>
<td></td>
</tr>
</tbody>
</table>

In order to identify those aspects of technique which characterise bowlers with the highest peak forces in their lower back, a second regression analysis was performed in which the input parameters consisted solely of kinematic variables (Table 9.3). As would be expected, the variation in the peak resultant force in the lower back explained was lower than when peak ground reaction force was included. The best individual predictor of peak lower back force was the foot-strike indicator; bowlers who were more dorsi-flexed at front foot contact experienced lower peak forces. The best two-parameter predictive equation consisted of the foot-strike indicator and plant angle. However, there was insufficient evidence for the inclusion of the plant angle term in the predictive equation using the sample of data collected in this study (P = 0.108). The best predictive equation obtained explained 58.4% of the variation in peak lower back force and consisted of foot-strike indicator, plant angle and run-up speed.
Table 9.3 – Details of the predictive equations obtained explaining the variation in peak resultant lower back force when only kinematic technique parameters were used.

<table>
<thead>
<tr>
<th>Model</th>
<th>Technique Variable(s)</th>
<th>Coefficient</th>
<th>P-Value</th>
<th>Percentage Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Foot-strike indicator</td>
<td>-0.049</td>
<td>0.032</td>
<td>23.1</td>
</tr>
<tr>
<td>2</td>
<td>Foot-strike indicator</td>
<td>-0.042</td>
<td>0.055</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.117</td>
<td>0.108</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Foot-strike indicator</td>
<td>-0.062</td>
<td>0.003</td>
<td>58.4</td>
</tr>
<tr>
<td></td>
<td>Plant angle</td>
<td>-0.203</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Run-up speed</td>
<td>1.402</td>
<td>0.008</td>
<td></td>
</tr>
</tbody>
</table>

9.5 DISCUSSION

The results of this study indicate that peak forces in the lower back, during the front foot contact phase of the fast bowling action, are largely dependent on peak ground reaction forces. These results support the assumption made in previous studies, that high peak forces occur in the lower back during the initial part of the front foot contact phase. This coincides with the period of the action in which lower trunk movements known to produce high contralateral facet joint forces typically peak. The strong link between the peak forces in the lower back and the peak ground reaction forces would suggest bowlers who are likely to have the highest peak forces in their lower back could be identified using just a force plate. Peak forces in the lower back were also observed to be linked to: plant angle; the amount of hip flexion from front foot contact until ball release; and the knee angle at front foot contact.

A smaller plant angle was linked to higher peak forces in the lower back; a similar link between plant angle and peak vertical ground reaction forces has been reported previously (Chapter 7). This observation also coincides with the reported trend for bowlers who have suffered from a lower back stress fracture to have a more extended hip at front foot contact (Portus et al., 2004). This is perhaps partially due to the orientation of the trunk relative to the line of the front leg. If the front leg and trunk are aligned at front foot contact, as is more the case for bowlers with a smaller plant angle, the forces are likely to be transmitted up the length of the spine. Bowlers with a larger plant angle have their trunk less aligned with the front leg and the force is more likely to be partially absorbed by the tissues of the thorax.
Previous researchers have suggested that the use of a technique in which the front knee flexes during the front foot contact phase enables bowlers to dissipate the ground reaction forces and reduce the likelihood of injury. It has previously been reported that increased knee flexion within a group of elite fast bowlers has no significant effect on the peak ground reaction forces (Chapter 7). Instead increased knee flexion was associated with a decreased time to peak force (in both the vertical and braking directions). It was concluded that the knee flexion observed in many fast bowlers is likely to be a consequence of high peak ground reaction forces, as opposed to the knee action determining the magnitude of the peak ground reaction forces. The results of the current study indicate that a similar relationship is present between the peak forces in the lower back and the flexion of the front hip. Increased hip flexion, during the period from front foot contact until ball release, was linked to higher peak forces in the lower back. It should be highlighted that the amount of knee flexion calculated in these studies were during the entire period from front foot contact until ball release. Future studies should consider the motion of the hip and knee during the initial part of the front foot contact phase, up to the instant of the peak force in the lower back, in order to determine the mechanical relationship between the peak forces and the motion of the front leg.

The use of a more flexed knee at front foot contact was also observed to be associated with higher peak forces in the lower back. There is no obvious mechanical explanation of this relationship. This suggests a more flexed knee is perhaps associated with an aspect of technique which has not been considered in this study, for instance the upper body orientation. This suspicion is further fuelled by the relatively high P-value (P = 0.066) associated with this parameter in the predictive equation.

The removal of the peak resultant ground reaction force from the predictive equation enabled kinematic aspects of bowling technique characterising bowlers with the highest peak lower back forces to be identified. The bowlers with the highest peak forces in their lower back were observed to have a quicker run-up, a more plantar-flexed foot at front foot contact and a smaller plant angle. These three variables have been previously been identified as the best predictors of the peak vertical ground reaction force in fast bowlers (Chapter 7).

The inverse dynamics analysis performed in this study indicated the time to peak force in the lower back was very closely linked to the ground reaction forces, with the peak ground
reaction force and the peak lower back force typically occurring at the same instant (Figure 9.5). In reality, this may not be the case due to soft tissue motion and joint compression delaying the transmission of the peak force up the leg. Future studies should look to incorporate wobbling masses into an inverse dynamics analysis in order to calculate the time to peak force in the lower back more accurately.

The results of this investigation represent relationships between front leg technique, peak ground reaction forces and peak forces in the lower back observed for a group of elite fast bowlers. Although speculations regarding the mechanics of the relationships can be made based on these results, future studies should address these relationships directly by means of a simulation model incorporating wobbling masses. Estimations of the peak lower back force in fast bowlers should also be combined with the orientation of the lower back at this instant, potentially enabling those bowlers who are at the greatest risk of developing lower back injuries to be identified.

9.6 CONCLUSIONS

This study has addressed the relationships between the peak forces in the lower back of fast bowlers, during the early part of the front foot contact phase, and the motion of the front leg between front foot contact and ball release. The results indicate peak forces in the lower back are determined predominantly by the magnitude of the ground reaction forces. This suggests bowlers with high forces in their lower back could be identified using just a force plate, rather than requiring three-dimensional inverse dynamics to be performed. It also appears that peak forces in the lower back are predominantly determined by the bowlers’ initial conditions at the instant of front foot contact, rather than their technique during the front foot contact phase. Future work should look to address the likelihood of lower back injuries in fast bowlers by considering the peak forces in the back as well as the orientation of the spine during this period of the action.
SUMMARY AND CONCLUSIONS

The purpose of the present study was to analyse the fast bowling action in order to gain an understanding of the interactions between aspects of fast bowling technique, ball release speed and the forces exerted on the bowler. Within this chapter, the extent to which this aim has been achieved through the development and application of a multi-segment representation of a fast bowler, is considered. The methods used within the study are also summarised and limitations and potential improvements are identified. The research questions posed in Chapter 1 are addressed and potential future studies are proposed.

10.1 THESIS SUMMARY

10.1.1 DATA COLLECTION

Data were collected for a group of thirty elite fast bowlers in an indoor cricket practice facility (Sections 3.1 and 3.2). Each bowler performed six maximum velocity bowling trials, striking the force plate with their front foot during the front foot contact phase of the bowling action. A Vicon Motion Analysis System was used to collect synchronous kinematic (300 Hz) and kinetic data (1200 Hz) for each trial performed. Force data (kinetic) were also collected within Kistler’s BioWare v.3.22 software (1008 Hz). A marker on the ball enabled ball release speed and the instant of ball release to be calculated.

Unfortunately two subjects withdrew from the study as they were unable to bowl at maximum pace without discomfort from recent injuries. Furthermore, an additional eight subjects were eliminated from the study as they did not perform a sufficient number of deliveries in which the force plate was hit cleanly during front foot contact with crucial markers remaining affixed to the body. Small sample sizes are an inherent problem when studying elite populations. Unfortunately there was insufficient time available to ensure all bowlers performed three trials which could be used in the study and it was felt that bowlers may change from their natural technique if they were under pressure to hit the force plate.
Subject-specific segmental inertia parameters were determined using the geometric model of Yeadon (1990) (Section 3.5). This model has been used successfully in previous studies (e.g. Wilson, 2003; Glynn, 2007), enabling subject specific parameters to be determined with little inconvenience caused to the subjects.

10.1.2 DATA PROCESSING

The best three trials – maximum velocity deliveries with minimal marker loss and front foot contact on the force plate – were identified for each bowler for inclusion in the study. Although every effort was made to maximise the accuracy of the data collected, the dynamic nature of the bowling action meant inevitably there were some small gaps in the tracked marker positions. These gaps were small in duration and were filled using one of a selection of methods, depending on the specific situation (Section 3.6.2).

Some noise within the kinematic data collected using a marker based motion tracking system is inevitable. This can be a consequence of marker wobble due to skin movement or the inability of the system to track all markers accurately at every point during the delivery action. Although the marker trajectories were relatively smooth, this noise was magnified when differentiated in order to calculate velocities and accelerations. All kinematic data were filtered using a Butterworth filter (double-pass) with a low pass cut-off frequency of 30 Hz (Section 3.6.3).

10.1.3 DATA ANALYSIS

A whole-body inverse dynamics analysis of the bowling action was performed within Vicon’s BodyBuilder software (Section 4.1). The human body was represented as a system of 18 rigid segments: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two-segment foot. Joint centres were located using a predictive approach, typically the mid-point of two strategically placed markers (Section 4.3). To reduce errors in the location of the joint centres, markers were positioned when the bowler was in a typical position as occurs during the bowling action – e.g. arm overhead when positioning the shoulder markers. A three-dimensional local
A coordinate system was defined for each segment, allowing segment orientations and joint angles to be calculated (Section 4.5).

The mass, position of the centre of mass and the three principal moments of inertia of each segment were defined using the output from the geometric model of Yeadon (1990) for each bowler (Section 4.6). This enabled the calculation of the whole body centre of mass for each bowler and the subsequent calculation of the forces and moments acting at each joint.

Parameters describing aspects of fast bowling technique were calculated for each trial (Section 4.8), these included: run-up speed and ball release speed; front leg motion; motion of the back; position of the bowling arm; and a selection of cricket specific parameters used for action classification. Kinetic parameters describing peak forces, time to peak force, loading rates and impulse in the vertical and braking directions were also calculated for each trial.

Internal forces and moments at each joint were calculated using inverse dynamics; the body was represented as a system of rigid segments connected by pin joints (Section 4.7). Unfortunately, this method of calculating joint moments was prone to oscillations during the initial part of the front foot contact phase. It is thought that this may be a consequence of modelling the joints as pin-joints, in reality the contact point between bones at a joint is an area, rather than just a point, and is likely to move as the joint’s orientation changes. As such, unrealistic oscillations were observed in the joint moments calculated. The joint forces calculated provided an estimation of the relative forces experienced by different bowlers enabling comparison between techniques. To investigate the mechanics of the action in more detail with regard to the forces in the body, wobbling masses and joint compression should be included within future models.

The intra-trial reliability of the parameters calculated was assessed (Section 4.9), the very good between-trial reliability for all data meant a representative value of each parameter could be calculated by taking a mean value from the three trials recorded. Correlations were assessed using a two-tailed Pearson’s product moment coefficient and the effect of interactions between technique parameters on a particular outcome measure were assessed using linear regression. A limitation of this approach was the relatively small sample size included in this study, which restricted the number of predictive parameters which could be identified. However, the results obtained explain the majority of the variation in each
outcome measure and give an indication of the mechanics of the bowling action. It should be noted that this study has addressed linear relationships between technique variables, future work could consider the possibility of other forms of associations.

10.2 RESEARCH QUESTIONS

The research questions posed in Chapter 1 were addressed in detail in Chapters 6 – 9. The full body inverse dynamics analysis performed enabled the mechanics of the fast bowling action to be more thoroughly understood. The research questions are restated below and the results summarised.

1. Which aspects of fast bowling technique characterise the fastest bowlers?

Previous researchers have identified a number of aspects of fast bowling technique which are linked to ball release speed. However, there is currently no consensus regarding which aspects of technique are the most important, nor has the effect of interactions between aspects of technique been considered. Four of these technique parameters were identified which explained 73.6% of the variation observed in ball release speed among the group of elite bowlers. These parameters were: run-up speed; shoulder angle at front foot contact; the amount of thoracic flexion between front foot contact and ball release; and the front knee angle at the instant of ball release. The results indicate that the quickest bowlers have a quicker run-up and maintain a straighter front knee throughout the front foot contact phase. The fastest bowlers also exhibited larger amounts of thoracic flexion between front foot contact and appeared to delay the onset of upper arm circumduction.

2. What is the effect of the front leg technique used by fast bowlers on the ground reaction forces during the front foot contact phase?

The variation in peak vertical force observed among a group of elite fast bowlers was best explained (63% of the variation) using three parameters describing the initial conditions at the instant of front foot contact. Higher peak vertical forces were associated with a quicker run-up speed, a more plantar flexed foot at front foot contact and a smaller plant angle.
The run-up speed and the manner of foot-strike were also the best predictors of peak braking force. An increased time to peak force, in both the vertical and braking directions, was associated with a more dorsi-flexed foot at front foot contact and a smaller amount of knee flexion during the period from front foot contact until ball release. The results suggest the flexion of the front knee observed in the majority of bowlers is as a consequence of the high peak ground reaction forces, rather than knee flexion facilitating dissipation of the ground reaction forces as has been suggested in previous studies.

3. Do the fastest bowlers have the highest peak ground reaction forces and loading rates?

Faster ball release speeds were observed to be significantly correlated with lower loading rates (in both the vertical and braking directions). Furthermore, an almost significant correlation was observed between lower peak vertical ground reaction forces and faster release speeds. These results contradict previous reports of higher ball release speeds being linked to both higher peak forces and loading rates (Portus et al., 2004). The results of the current study suggest the ground reaction force characteristic most closely linked to ball release speed is the braking impulse between front foot contact and ball release. Bowlers appeared to generate this larger braking impulse by means of a larger plant angle at the instant of front foot contact.

4. What is the effect of the front leg technique used and the ground reaction forces on the peak force in the lower back during the front foot contact phase of the fast bowling action?

The peak resultant force at the base of the lumbar spine was observed to be largely dependent on the peak ground reaction force, explaining 93.9% of the variation in the peak lower back force. Higher peak forces in the lower back were also found to be linked to a smaller plant angle, larger amounts of hip flexion during the period from front foot contact until ball release, and a more flexed knee at front foot contact.
10.3 FUTURE STUDIES

Additional research questions that are prompted by the work in this thesis include:

- What is the effect of changing individual aspects of bowling technique on the ball release speed of an individual bowler?
- What are the physical requirements of using techniques identified in this study as being linked to faster ball release speeds?
- Why do the majority of bowlers flex their front knee and hip during the early part of the front foot contact phase?
- How does the motion of the front knee during the period from front foot contact until peak ground reaction force affect the characteristics of the ground reaction forces?
- Are aspects of bowling technique considered in this study linked to common injuries in fast bowlers (e.g. posterior ankle impingement, lumbar stress fracture, or knee osteochondral defects)?

10.4 CONCLUSIONS

The aim of the present study was to analyse the fast bowling action in order to gain an understanding of the mechanics of the movement, in particular how aspects of fast bowling technique affect ball release speed and the forces exerted on the bowler. To achieve this, a three-dimensional inverse-dynamics analysis was performed on a group of elite fast bowlers. It was found that the quickest bowlers had a quicker run-up and maintained a straighter front knee throughout the front foot contact phase. The fastest bowlers also exhibited larger amounts of thoracic flexion between front foot contact and ball release and appeared to delay the onset of upper arm circumduction. Faster ball release speeds were associated with a larger braking impulse between front foot contact and ball release in addition to lower peak loading rates. The results also indicate that the peak ground reaction forces and the peak forces in the lower back are determined predominantly by the initial orientation of the front leg at the instant of front foot contact.
REFERENCES


## APPENDIX 1

### SUBJECT DETAILS

<table>
<thead>
<tr>
<th>Subject</th>
<th>Year</th>
<th>Mass (kg)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2007</td>
<td>87.6</td>
<td>1.983</td>
</tr>
<tr>
<td>2</td>
<td>2007</td>
<td>72.5</td>
<td>1.861</td>
</tr>
<tr>
<td>3</td>
<td>2007</td>
<td>81.9</td>
<td>2.002</td>
</tr>
<tr>
<td>4</td>
<td>2007</td>
<td>79.3</td>
<td>1.864</td>
</tr>
<tr>
<td>5</td>
<td>2007</td>
<td>83.0</td>
<td>1.990</td>
</tr>
<tr>
<td>6</td>
<td>2007</td>
<td>84.0</td>
<td>1.815</td>
</tr>
<tr>
<td>7</td>
<td>2008</td>
<td>82.2</td>
<td>1.909</td>
</tr>
<tr>
<td>8</td>
<td>2008</td>
<td>79.5</td>
<td>1.885</td>
</tr>
<tr>
<td>9</td>
<td>2008</td>
<td>80.4</td>
<td>1.797</td>
</tr>
<tr>
<td>10</td>
<td>2008</td>
<td>88.8</td>
<td>2.034</td>
</tr>
<tr>
<td>11</td>
<td>2008</td>
<td>92.6</td>
<td>1.826</td>
</tr>
<tr>
<td>12</td>
<td>2008</td>
<td>73.1</td>
<td>1.830</td>
</tr>
<tr>
<td>13</td>
<td>2008</td>
<td>70.4</td>
<td>1.862</td>
</tr>
<tr>
<td>14</td>
<td>2008</td>
<td>86.0</td>
<td>1.795</td>
</tr>
<tr>
<td>15</td>
<td>2008</td>
<td>85.8</td>
<td>1.867</td>
</tr>
<tr>
<td>16</td>
<td>2009</td>
<td>87.0</td>
<td>1.935</td>
</tr>
<tr>
<td>17</td>
<td>2009</td>
<td>88.0</td>
<td>1.809</td>
</tr>
<tr>
<td>18</td>
<td>2009</td>
<td>85.5</td>
<td>1.891</td>
</tr>
<tr>
<td>19</td>
<td>2009</td>
<td>64.0</td>
<td>1.746</td>
</tr>
<tr>
<td>20</td>
<td>2009</td>
<td>78.0</td>
<td>1.836</td>
</tr>
</tbody>
</table>
This study comprises a biomechanical analysis of human movement. This analysis requires kinematic (how you are moving) data of the bowling action and also a number of movements that determine the range of motion of the back and shoulders.

The data of actual human movements are required to give detailed information about the current techniques used. The data collected will then be used to understand and explain techniques currently used, determine the contributions of different techniques to performance and injury as well as to optimise performance.

The kinematic data will be obtained in a number of different ways:

- Video and cinematographic recordings.
- Automatic displacement acquisition system. This is similar to being videoed but reflective markers will be taped to you and only their image recorded.
- Joint angle measurements using a goniometer.

The subject specific parameters may be obtained from:

- Anthropometric measurements. Measuring certain arm condition(s) (such as ‘straight’ and ‘fully flexed’) with the automatic motion capture or through the use of a goniometer.

Data will be acquired in the ECB National Cricket Centre at Loughborough University. The data collection session will last no longer than two hours, with the subject actively involved for only a fraction of the total time:

- Actual performance of movements: 20 minutes
- Anthropometric measurements: 30 minutes
The study in which you have been invited to participate will involve a biomechanical analysis of your bowling action. The study will involve you being videoed, using a number of different cameras, as you bowl and carry out a number of motions which give a measure of the range of motion of your back and shoulders.

It may be necessary to shave certain areas of your body to attach monitoring equipment using adhesive tape. The data collected will be used to help increase our understanding of the mechanics of human movements.

You will perform the data collection in a suitable environment. The risk of injury during the data collection will be minimal since we will only ask you to perform movements with which you are familiar and comfortable. It is considered that no increased risks, discomforts or distresses are likely to result from the data collection of human movements above those associated with the normal performance of those movements.

The information obtained from the study will be collected and stored in adherence with the Data Protection Act. Whilst certain personal and training information will be required, you will be allocated a reference number to ensure that your identity and personal details will remain confidential. Video recordings will be stored in the video analysis room to which access is restricted to members of the biomechanics research team. The video images will be digitised and only the numerical values will be used in published work, not the images themselves. On occasion video images may be required. In such and instance we will seek your written permission to use such images and you are perfectly free to decline. Video recordings will be kept for three years after publication of the study. If you agree to take part in the study, you are free to withdraw from the study at any stage, with or without having to give any reasons. A contact name and phone number will be provided to you for use if you have any queries about any part of your participation in the study.
PRE-SELECTION MEDICAL QUESTIONNAIRE

LOUGHBOROUGH UNIVERSITY
DEPARTMENT OF PHYSICAL EDUCATION, SPORTS SCIENCE AND
RECREATION MANAGEMENT

Please read through this questionnaire, BUT DO NOT ANSWER ANY OF THE QUESTIONS YET. When you have read right through, there may be questions you would prefer not to answer. Assistance will be provided if you require it to discuss any questions on this form. In this case please tick the box labelled “I wish to withdraw” immediately below. Also tick the box labelled “I wish to withdraw” if there is any other reason for you not to take part.

Tick appropriate box

I wish to withdraw

I am happy to answer the questionnaire

If you are happy to answer the questions posed below, please proceed. Your answers will be treated in the strictest confidence.

1. Are you at present recovering from any illness or operation? YES/NO*

2. Are you suffering from or have you suffered from or received medical treatment for any of the following conditions?

   a. Heart or circulation condition
      YES/NO*

   b. High blood pressure
      YES/NO*

   c. Any orthopaedic problems
      YES/NO*

   d. Any muscular problems
      YES/NO*
e. Asthma or bronchial complaints
   YES/NO*

3. Are you currently taking any medication that may affect your
   YES/NO*
   participation in the study?

4. Are you recovering from any injury?
   YES/NO*

5. Are you epileptic?
   YES/NO*

6. Are you diabetic?
   YES/NO*

7. Are you allergic to sticking plasters?
   YES/NO*

8. Do you have any other allergies? If yes, please give details below
   YES/NO*
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   …

9. Are you aware of any other condition or complaint that may be affected by
   participation in this study? If so, please state below;
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   ……………………………………………………………………………………………..
   …

   * Delete as appropriate
INFORMED CONSENT FORM (SUBJECTS)

PURPOSE
To obtain kinematic data during human movements

PROCEDURES
The kinematic data of human movements will be obtained using:
- Video and cinematographic recordings
- Automatic displacement acquisition system
- Joint angle measurements using a goniometer

ACTIVITIES
- Bowling
- Range of motion trials

A number of trials will be requested with suitable breaks to minimise fatigue and boredom.

During the measurements two researchers will be present, at least one of whom will be of the same sex as you.

QUESTIONS
The researchers will be pleased to answer any questions you may have at any time.

WITHDRAWAL
You are free to withdraw from the study at any stage, with or without having to give any reasons.

CONFIDENTIALITY
Your identity will remain confidential in any material resulting from this work. Video recordings will be stored in the video analysis room to which access is restricted to members of the biomechanics research team. The video images will be digitised and only the numerical values will be used in published work, not the images themselves. On occasion video images may be required. In such an instance we will seek your written permission to use such images and you are perfectly free to decline. Video recordings will be kept for three years after publication of the study.

I have read the outline of the procedures which are involved in this study, and I understand what will be required by me. I have had the opportunity to ask for further information and for clarification of the demands of each of the procedures and understand what is entailed. I am aware that I have the right to withdraw from the study at any time with no obligation to give reasons for my decision. As far as I am aware I do not have any injury or infirmity which would be affected by the procedures outlined.

Name …………………………………………
Signed ………………………………………… (subject)
Date ………………………………
In the presence of:
Name …………………………………………
APPENDIX 3
MARKER POSITIONS

The marker positions used in this study are illustrated in the pictures below, details of the exact position of each marker are also provided.

HEAD

A head-band with four markers attached was placed over the subject’s head; the front two markers were positioned on the temples. The positions of the two markers on the back of the head were not so critical, they were positioned so they were level when the subject’s neck was straight.

PELVIS

<table>
<thead>
<tr>
<th>Marker #</th>
<th>Marker Label</th>
<th>Marker Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RASI</td>
<td>Bony protrusion of the right anterior super iliac</td>
</tr>
<tr>
<td>2</td>
<td>LASI</td>
<td>Bony protrusion of the left anterior super iliac</td>
</tr>
<tr>
<td>3</td>
<td>RPSI</td>
<td>Dimple created by the right posterior super iliac</td>
</tr>
<tr>
<td>4</td>
<td>LPSI</td>
<td>Dimple created by the left posterior super iliac</td>
</tr>
<tr>
<td>5</td>
<td>LHIP</td>
<td>Position not crucial (only used for asymmetry purposes). Roughly level with the other pelvis markers and approximately above the hip joint centre</td>
</tr>
</tbody>
</table>
### THORAX

<table>
<thead>
<tr>
<th>Marker #</th>
<th>Marker Label</th>
<th>Marker Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>LUM1</td>
<td>First lumbar vertebra. Can be located by initially finding L5, which lies between the two PSIS. From here you can count up to L1.</td>
</tr>
<tr>
<td>7</td>
<td>T10</td>
<td>Tenth thoracic vertebra. Can count up from L1 (T12, T11, T10).</td>
</tr>
<tr>
<td>8</td>
<td>STRN</td>
<td>Centre of marker positioned over lower tip of sternum</td>
</tr>
<tr>
<td>9</td>
<td>CLAV</td>
<td>Centre of marker positioned over upper tip of clavicle</td>
</tr>
<tr>
<td>10</td>
<td>C7</td>
<td>Seventh cervical vertebra. This is the long cervical vertebra, which is particularly prominent when the subject bends their head forwards.</td>
</tr>
<tr>
<td>11</td>
<td>RBAK</td>
<td>Position not crucial, is just used for asymmetry. Somewhere in the centre of the right scapula</td>
</tr>
</tbody>
</table>

### ARMS

<table>
<thead>
<tr>
<th>Marker #</th>
<th>Marker Label</th>
<th>Marker Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>12, 13</td>
<td>SHOP</td>
<td>Posterior of shoulder.</td>
</tr>
<tr>
<td>14, 15</td>
<td>SHOA</td>
<td>Mid point of the posterior and anterior shoulder markers should define the Shoulder Joint Centre when the arm is pointing vertically upwards. Typically the anterior marker will be significantly higher than the posterior marker.</td>
</tr>
<tr>
<td>16, 17</td>
<td>SHOT</td>
<td>Top of shoulder, positioned on the acromion process</td>
</tr>
<tr>
<td>18, 19</td>
<td>ELBM</td>
<td>Medial side of elbow</td>
</tr>
<tr>
<td>20, 21</td>
<td>ELBL</td>
<td>Mid point of the 2 elbow markers is the Elbow Joint Centre – this should be done with the elbow fully straightened – i.e. in the part of the elbow’s range of motion we want to be most accurate. A line joining the 2 elbow markers should be at ninety degrees to the frontal plane of the Humerus</td>
</tr>
<tr>
<td>22, 23</td>
<td>WRA</td>
<td>Mid point of the 2 wrist markers is the Wrist Joint Centre. A line joining the 2 wrist markers should be at ninety degrees the frontal plane of the Radius</td>
</tr>
<tr>
<td>24, 25</td>
<td>WRB</td>
<td>Little finger side of wrist.</td>
</tr>
<tr>
<td>26, 27</td>
<td>HND</td>
<td>Back of hand, on the hand’s longitudinal axis – the line between the Wrist Joint Centre and the Middle Finger. This marker should be positioned 2cm below the middle base knuckle</td>
</tr>
</tbody>
</table>
### LEGS

<table>
<thead>
<tr>
<th>Marker #</th>
<th>Marker Label</th>
<th>Marker Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>28, 29</td>
<td>TOE</td>
<td>On the centre line of foot Marker’s centre was 3cm from tip of big toe</td>
</tr>
<tr>
<td>30, 31</td>
<td>MTPM</td>
<td>Medial side of the MTP joint</td>
</tr>
<tr>
<td>32, 33</td>
<td>MTPL</td>
<td>Lateral side of the MTP joint</td>
</tr>
</tbody>
</table>
|          |              | • Mid point of the 2 MTP markers is the MTP Joint Centre  
|          |              | • A line joining the 2 MTP markers should be at ninety degrees to the frontal plane of the Foot |
| 34, 35   | ANKM         | Medial side of ankle |
| 36, 37   | ANKL         | Lateral side of ankle |
|          |              | • Mid point of the 2 ankle markers is the Ankle Joint Centre  
|          |              | • A line joining the 2 ankle markers should be at ninety degrees to the frontal plane of the Tibia |
| 38, 39   | HEE          | Centre line of foot, placed on back of heel of shoe and at similar height to Toe marker |
| 40, 41   | KNEM         | Medial side of knee |
| 42, 43   | KNEL         | Lateral side of knee |
|          |              | • Mid point of the 2 knee markers is the Knee Joint Centre  
|          |              | • A line joining the 2 knee markers should be at ninety degrees to the frontal plane of the Femur |
APPENDIX 4
FILTERING

This section provides an illustration of the filtering performed on the kinematic data and its effect on the position, velocity and acceleration of a marker. The illustrations provided are for the medial ankle marker on the front foot during the initial part of the front foot contact phase, when the impact with the ground occurs.

<table>
<thead>
<tr>
<th>POSITION</th>
<th>VELOCITY</th>
<th>ACCELERATION</th>
</tr>
</thead>
</table>

The method used by Winter (1990) suggested a cut-off frequency in the range of 15 – 25 Hz should be applied to the marker positions. As the data collected in this study had a higher spatial resolution than that used by Winter, a slightly higher cut-off frequency of 30 Hz was applied to the position data. This meant that there was less signal distortion, but more noise could pass through the filter. Applying a 30 Hz cut-off to all marker trajectories, from front foot contact until ball release, produced a maximum difference of 4 mm between the raw position and the filtered position of the marker.
APPENDIX 5

DIRECTION COSINE MATRIX

This section describes the direction cosine matrix (DCM) used to calculate the orientation of the lumbar spine relative to a zero reference. This methodology is equivalent to that used by Burnett et al., (1998).

The DCM performs the coordinate transformation of a vector from one set of coordinate axes \((x_1', x_2', x_3')\) into a vector in another set of axes \((y_1', y_2', y_3')\).

The order of the axis rotations required to bring \(y'\) into coincidence with \(x'\) is first a rotation about \(y_1'\) through the roll angle \((\phi)\), second, a rotation about \(y_2'\) through the pitch angle \((\theta)\) and finally a rotation about \(y_3'\) through the yaw angle \((\psi)\).

\[
\begin{bmatrix}
  y_1' \\
  y_2' \\
  y_3'
\end{bmatrix} = DCM \begin{bmatrix}
  x_1' \\
  x_2' \\
  x_3'
\end{bmatrix}
\]

\[
\begin{bmatrix}
  y_1' \\
  y_2' \\
  y_3'
\end{bmatrix} = \begin{bmatrix}
  1 & 0 & 0 \\
  0 & \cos \phi & \sin \phi \\
  0 & -\sin \phi & \cos \phi
\end{bmatrix} \begin{bmatrix}
  \cos \theta & 0 & -\sin \theta \\
  \cos \psi & \sin \psi & 0 \\
  -\sin \psi & \cos \psi & 0
\end{bmatrix} \begin{bmatrix}
  x_1' \\
  x_2' \\
  x_3'
\end{bmatrix}
\]

Combining these three axis transformation matrices defines the following DCM. There is more than one possible DCM, but only one per order of the axis transformations.

\[
DCM = \begin{bmatrix}
  \cos \theta \cos \psi & \cos \theta \sin \psi & -\sin \theta \\
  \left(\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi\right) & \left(\sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi\right) & \sin \phi \cos \theta \\
  \left(\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi\right) & \left(\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi\right) & \cos \phi \cos \theta
\end{bmatrix}
\]
To determine $\phi, \theta, \psi$ from the DCM, the following equations are used:

$$\phi = a \tan \left( \frac{DCM(2,3)}{DCM(3,3)} \right)$$

$$\theta = a \sin(-DCM(1,3))$$

$$\psi = a \tan \left( \frac{DCM(1,2)}{DCM(1,1)} \right)$$

This general theory can be applied to the specific problem of expressing the orientation of the lumbar spine relative to a zero reference, rather than body coordinates which are dependent on the positioning of the markers, as follows.

$$\begin{bmatrix} y'_1 \\ y'_2 \\ y'_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} x'_1 \\ x'_2 \\ x'_3 \end{bmatrix}$$

$y'$ = new axes

$x'$ = original axes

$$[y'] = A[x']$$

$y'$ = actual xyz coordinates (relative to a zero reference frame)

$x'$ = body coordinates (dependent on marker positioning)

We have 2 sets of data:

1. Motion during delivery trial
2. Neutral position – when have no flexion, rotation or twist

(1) $\Rightarrow [y'] = R_1[x'_1]$

(2) $\Rightarrow [y'] = R_2[x'_2]$

So we can write,

$$[y'] = R_1[x'_1] = R_2[x'_2].$$
A crucial property of transformation matrices of orthonormal (i.e. all at right angles to each other) reference frames is

\[ R_{1-2}^{-1} = R_{1-2}^T = R_{2-1} \]

Using this we can express angles relative to the neutral position coordinates, \( x_2' \) (zero reference),

\[ [x_2'] = R_2^T R_1 [x_1'] . \]
APPENDIX 6

BODY LANGUAGE CODE

{*Written by Peter Worthington, 2008*}
{*This model was developed to be used in the 3D analysis of bowling techniques - kinematic and kinetic*}

{*Initialisations*}

OptionalPoints(LFHD,RFHD,LBHD,RBHD)
OptionalPoints(C7,T10,LUM1,CLAV,STRN,LBAK)
OptionalPoints(LSHOP,LSHOA,LSHOT,LELBL,LELB,M,LWRA,LWRB,LHND)
OptionalPoints(RSHOP,RSHOA,RSHOT,RELBL,RELBM,RWRA,RWBR,RHND)
OptionalPoints(RASI,LASI,RPSI,LPSI,LHIP)
OptionalPoints(RKNEM,RKNEL,RANKL,RANKM,RMTPM,RMTPL,RHEE,RTOE)
OptionalPoints(LKNEM,LKNEL,LANKL,LANKM,LMTPM,LMTPL,LHEE,LTOE)
OptionalPoints(RSHOP,RSHO,LSHOT,RELBM,RWRA,RWRA,RWBR,RHND)
OptionalPoints(RASI,LASI,RPSI,LPSI,LHIP)
OptionalPoints(RKNEM,RKNEL,RANKL,RANKM,RMTPM,RMTPL,RHEE,RTOE)

{*Set Deadband, except for static trials*}
If $Static<>1$ Deadband = $Deadband$ EndIf

Gorigin = {0,0,0}
Global = [Gorigin, {1,0,0}, {0,0,1}, xyz]
DisplayAxes(Global)

*KINEMATICS*

Calculate certain Joint Centres using pairs of markers (strategically positioned)*
RSHO = (RSHOP+RSHOA)/2
LSHO = (LSHOP+LSHOA)/2
RELBM = (RELBM+RELBM)/2
LELBL = (LELBL+LELBL)/2
RWRA = (RWRA+RWRA)/2
LWRA = (LWRA+LWRA)/2
RKNEM = (RKNEM+RKNEM)/2
LKNEM = (LKNEM+LKNEM)/2
RANK = (RANKM+RANKM)/2
LANK = (LANKM+LANKM)/2
RMTPM = (RMTPM+RMTPM)/2
LMTPM = (LMTPM+LMTPM)/2
OUTPUT
(RSHO,LSHO,RELB,LELB,RWRI,LWRI,RKNE,LKNE,RANK,LANK,RMTP,LMTP)

{*---------------------------------------------------------------*}

{*Pelvis*}
{*=======*}

If $Static==1 Then
  LLegLength = DIST(LASI,LKNEL)+DIST(LKNEL,LANKL)  
  RLegLength = DIST(RASI,RKNEL)+DIST(RKNEL,RANKL)  
  MP_LegLength = (LLegLength+RLegLength)/2  
  PARAM(MP_LegLength)
EndIf

SACR = (LPSI+RPSI)/2  
PELF = (LASI+RASI)/2  
Pelvis = [PELF,RASI-LASI,SACR-PELF,xzy]
LATD = 0.1288*MP_LegLength-48.56  
RATD = LATD

C = MP_LegLength*0.115-15.3  
InterASISDist=DIST(LASI,RASI)  
aa = InterASISDist/2  
mm = $MarkerDiameter/2  
COSBETA = 0.951  
SINBETA = 0.309  
COSTHETA = 0.880  
SINTHETA = 0.476  
COSTHETASINBETA = COSTHETA*SINBETA  
COSTHETACOSBETA = COSTHETA*COSBETA

LHJC = {C*SINTHETA - aa,C*COSTHETASINBETA - (LATD + mm) * COSBETA,  
         -C*COSTHETACOSBETA - (LATD + mm) * SINBETA}*Pelvis

RHJC = {-C*SINTHETA + aa,C*COSTHETASINBETA - (RATD + mm) * COSBETA,  
         -C*COSTHETACOSBETA - (RATD + mm) * SINBETA}*Pelvis

OUTPUT(LHJC,RHJC)  
Pelvis = (LHJC+RHJC)/2 + Attitude(Pelvis)  
DisplayAxes(Pelvis)

LOWJC = SACR+0.2*(PELF-SACR)  
OUTPUT(LOWJC)

{*Femura*}
{*======*}

LFemur = [LKNE,LHJC-LKNE,LKNEL-LKNE,zyx]  
RFemur = [RKNE,RHJC-RKNE,RKNE-RKNEL,zyx]
DisplayAxes(LFemur)
DisplayAxes(RFemur)

{*Tibiae*}
{*=*=*=*=*=*=}

LTibia = [LANK,LKNE-LANK,LANKL-LANK,zyx]
RTibia = [RANK,RKNE-RANK,RANK-RANKL,zyx]
DisplayAxes(LTibia)
DisplayAxes(RTibia)

{*Foot and Toe Segments*}
{*=*=*=*=*=*=*=*=*=*=*=*=*=*=*}

LFoot = [LMTP,LANK-LMTP,LMTPL-LMTP,zyx]
RFoot = [RMTP,RANK-RMTP,RMTP-RMTPL,zyx]

LToes = [LTOE,LMTP-LTOE,LMTPL-LMTP,zyx]
RToes = [RTOE,RMTP-RTOE,RMTP-RMTPL,zyx]

If $Static == 1 Then
  If $StaticFootFlat == 1 Then
    LRF = {1(LANK),2(LANK),3(LMTP)}
    RRF = {1(RANK),2(RANK),3(RMTP)}
    LFootRef = [LMTP,LRF-LMTP,LMTPL-LMTP,zyx]
    RFootRef = [RMTP,RRF-RMTP,RMTP-RMTPL,zyx]
  EndIf
  MP_LToeFlexOS = 1(<LFootRef,LToes,xyz>)
  MP_RToeFlexOS = 1(<RFootRef,RToes,xyz>)
  PARAM(MP_LToeFlexOS,MP_RToeFlexOS)
EndIf

LToes = ROT(LToes,1(LToes),MP_LToeFlexOS)
RToes = ROT(RToes,1(RToes),MP_RToeFlexOS)

DisplayAxes(LFoot)
DisplayAxes(RFoot)
DisplayAxes(LToes)
DisplayAxes(RToes)

{*Head Segment*}
{*=*=*=*=*=*=*=*=*=*=*=*=*=*=*}

LHead = (LFHD+LBHD)/2
RHead = (RFHD+RBHD)/2
BHead = (LBHD+RBHD)/2
FHead = (LFHD+RFHD)/2

TOPJC = C7+0.125*(FHead-BHead)
OUTPUT(TOPJC)

Head = [TOPJC,RHead-LHead,BHead-FHead,xyz]

If $Static == 1 Then
    HeadRef = [TOPJC,RHead-LHead,3(Global),xyz]
    If $StaticHeadLevel == 1 Then
        MP_HeadFlexOS = 1(<HeadRef,Head,xyz>)
    Else
        MP_HeadFlexOS = 0
    EndIf
    PARAM(MP_HeadFlexOS)
EndIf

Head = ROT(Head,1(Head),MP_HeadFlexOS)
DisplayAxes(Head)

{*Thorax segment*}
{*======*}

UThorax = (C7+CLAV)/2
LThorax = (T10+STRN)/2
FThorax = (CLAV+STRN)/2
BThorax = (C7+T10)/2
TRX0 = CLAV+0.125*(C7-CLAV)
Thorax = [TRX0,UThorax-LThorax,FThorax-BThorax,zxy]
DisplayAxes(Thorax)

{* The thoracic spine *}
{*=================*}

MIDJC = T10+0.125*(FThorax-BThorax)
OUTPUT(MIDJC)
upper_back_spine=[MIDJC,C7-LUM1,FThorax-BThorax,xyz]
DisplayAxes(upper_back_spine)

{* The lumbar spine *}
{*=================*}

lower_back_spine=[LOWJC,LUM1-SACR,STRN-LUM1,xyz]
DisplayAxes(lower_back_spine)

{*Humerus Segments*}
LHumerus = [LELB,LSHO-LELB,LELBL-LELB,zyx]
RHumerus = [RELB,RSHO-RELB,RELB-RELBL,zyx]
DisplayAxes(LHumerus)
DisplayAxes(RHumerus)

{*Radius (and Ulnar) Segments*}
LRadius = [LWRI,LELB-LWRI,LWRA-LWRI,zyx]
RRadius = [RWRI,RELB-RWRI,RWRI-RWRA,zyx]
DisplayAxes(LRadius)
DisplayAxes(RRadius)

{*Hand Segments*}
LHand = [LHND,LWRI-LHND,LWRA-LWRI,zyx]
RHand = [RHND,RWRI-RHND,RWRA-RWRA,zyx]

If $Static == 1 Then
  If $StaticWristStraight == 1 Then
    MP_LWristFlexOS = 1(<LRadius,LHand,xyz>)
    MP_RWristFlexOS = 1(<RRadius,RHand,xyz>)
    PARAM(MP_LWristFlexOS,MP_RWristFlexOS)
  EndIf
EndIf
LHand = ROT(LHand,LHand(1),MP_LWristFlexOS)
RHand = ROT(RHand,RHand(1),MP_RWristFlexOS)
DisplayAxes(LHand)
DisplayAxes(RHand)

COM_BODY_temp =
((LFemurMass*LFemurCOM)+(RFemurMass*RFemurCOM)+(LTibiaMass*LTibiaCOM)+
(SRTibiaMass*RTibiaCOM)+(LHumerusMass*LHumerusCOM)+(RHumerusMass*RHumerusCOM)+
(SLRadiusMass*LRadiusCOM)+(SRRadiusMass*RRadiusCOM)+(LHandMass*LHandCOM)+
(RHandMass*RHandCOM))
TOTAL_MASS = $LFemurMass + $RFemurMass + $LTibiaMass + $RTibiaMass +
$LHumerusMass + $RHumerusMass + $LRadiusMass + $RRadiusMass + $LHandMass +
$ToesMass + $LFootMass + $RFootMass + $LToesMass + $RToesMass
COM_BODY = COM_BODY_temp / TOTAL_MASS

OUTPUT(COM_BODY)

{*-----------------------------------------------------------------------------------------------------------------*}

{*Joint Angles*}
{*=================================*}

{*Thoracic Spine: lower_back_spine >> upper_back_spine*}
ThoracicAngles = -lower_back_spine,upper_back_spine,xyz>(-3)
ThoracicAngles = <180+ThoracicAngles(1),ThoracicAngles(2),ThoracicAngles(3)>

{*Lumbar Spine: Pelvis >> lower_back_spine*}
LumbarAngles = -Pelvis,lower_back_spine,xyz>(-3)
LumbarAngles = <180+LumbarAngles(1),LumbarAngles(2),LumbarAngles(3)>

OUTPUT(LumbarAngles,ThoracicAngles)

{*-----------------------------------------------------------------------------------------------------------------*}

{*Shoulders: Thorax >> Humeri*}
LShoulderAngles = -Thorax,LHumerus,xyz>
RShoulderAngles = -Thorax,RHumerus,xyz>(-1)

OUTPUT(LShoulderAngles,RShoulderAngles)

{*-----------------------------------------------------------------------------------------------------------------*}

{*Elbows: Humeri >> Radii*}
LElbowAngles = -LHumerus,LRadius,xyz>(-1)
LElbowAngles = <180+1(LElbowAngles),2(LElbowAngles),3(LElbowAngles)>
RElbowAngles = -RHumerus,RRadius,xyz>
RElbowAngles = <180+1(RElbowAngles),2(RElbowAngles),3(RElbowAngles)>

OUTPUT(LElbowAngles,RElbowAngles)

{*Knees: Femora >> Tibiae*}
LKneeAngles = -LFemur,LTibia,xyz>
LKneeAngles = <180+LKneeAngles(1),LKneeAngles(2),LKneeAngles(3)>
RKneeAngles = -RFemur,RTibia,xyz>(-1)
RKneeAngles = <180+RKneeAngles(1),RKneeAngles(2),RKneeAngles(3)>

OUTPUT(LKneeAngles,RKneeAngles)

{*Ankles: Tibiae >> Foot*}
LAnkleAngles = -LTibia,LFoot,xyz>(-1)
LAnkleAngles = <180+1(LAnkleAngles),2(LAnkleAngles),3(LAnkleAngles)>
RAnkleAngles = -RTibia,RFoot,xyz>
RAnkleAngles = <180+1(RAnkleAngles),2(RAnkleAngles),3(RAnkleAngles)>

OUTPUT(LAnkleAngles,RAnkleAngles)

OUTPUT(LKneeAngles,RKneeAngles,LAnkleAngles,RAnkleAngles)

{*-----------------------------------------------------------------------------------------------------------------*}
{*Hips: Pelvis >> Femora*}
LHipAngles = <$\text{Pelvis,LFemur,xyz}$>(-1)
LHipAngles$=\langle 180+1(\text{LHipAngles})\rangle,2(\text{LHipAngles}),3(\text{LHipAngles})$
RHipAngles = <$\text{Pelvis,RFemur,xyz}$>
RHipAngles$=\langle 180+1(\text{RHipAngles})\rangle,2(\text{RHipAngles}),3(\text{RHipAngles})$

OUTPUT(LHipAngles,RHipAngles)

{*---------------------------------------------------------------*}

{*Kinetics*}
{*========*}

VelocityThreshold = 10000
NN = $\$\text{BodyMass}$

ChestFredR = $\text{REACTION(ChestFred)}$
NeckForce = 1(ChestFredR)
NeckMoment = 2(ChestFredR)
ThoraxFredR = $\text{REACTION(ThoraxFred)}$
UpperBackForce = 1(ThoraxFredR)
UpperBackMoment = 2(ThoraxFredR)
PelvisFredR = $\text{REACTION(PelvisFred)}$
LowerBackForce = 1(PelvisFredR)
LowerBackMoment = 2(PelvisFredR)


RHumerusFredR = $\text{REACTION(RHumerusFred)}$
RShoulderForce = 1(RHumerusFredR)
RShoulderMoment = 2(RHumerusFredR)
LHumerusFredR = $\text{REACTION(LHumerusFred)}$
LShoulderForce = 1(LHumerusFredR)
LShoulderMoment = 2(LHumerusFredR)

OUTPUT(RShoulderForce,RShoulderMoment,LShoulderForce,LShoulderMoment)

RFemurFredR = $\text{REACTION(RFemurFred)}$
RHipForce = 1(RFemurFredR)
RHipMoment = 2(RFemurFredR)
LFemurFredR = $\text{REACTION(LFemurFred)}$
LHipForce = 1(LFemurFredR)
LHipMoment = 2(LFemurFredR)

OUTPUT(RHipForce,RHipMoment,LHipForce,LHipMoment)

RTibiaFredR = $\text{REACTION(RTibiaFred)}$
RKneeForce = 1(RTibiaFredR)
RKneeMoment = 2(RTibiaFredR)
LTibiaFredR = REACTION(LTibiaFred)
LKneeForce = 1(LTibiaFredR)
LKneeMoment = 2(LTibiaFredR)

OUTPUT(RKneeForce,RKneeMoment,LKneeForce,LKneeMoment)

RFootFredR = REACTION(RFootFred)
RAnkleForce = 1(RFootFredR)
RAnkleMoment = 2(RFootFredR)
LFootFredR = REACTION(LFootFred)
LAnkleForce = 1(LFootFredR)
LAnkleMoment = 2(LFootFredR)

OUTPUT(RAnkleForce,RAnkleMoment,LAnkleForce,LAnkleMoment)

RToesFredR = REACTION(RToesFred)
RToesForce = 1(RToesFredR)
RToesMoment = 2(RToesFredR)
LToesFredR = REACTION(LToesFred)
LToesForce = 1(LToesFredR)
LToesMoment = 2(LToesFredR)

OUTPUT(RToesForce,RToesMoment,LToesForce,LToesMoment)