

**School of Physiotherapy**

**Lumbar MRI Abnormalities and Muscle Morphology, Trunk  
Kinematics and Lower Back Injury in Professional Fast Bowlers in  
Cricket**

**Craig A Ranson**

**This thesis is presented for the degree of**

**Doctor of Philosophy**

**of**

**Curtin University of Technology**

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## **DECLARATION**

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:

A handwritten signature in cursive script, appearing to read "Capenson", is displayed within a light gray rectangular box.

Date: 08.02.08

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## **ABSTRACT**

Lower back injury remains the most important injury problem in professional cricket with lumbar stress fractures in fast bowlers accounting for the most lost playing time. Previous research has associated workload, paraspinal muscle asymmetry and technique factors with lower back injury in fast bowlers, however, preventative strategies such as workload directives and coaching guidelines have not reduced the incidence and prevalence of these injuries.

Recent developments in medical imaging technology have improved diagnosis of pathologies such as lumbar posterior bony element (partes interarticulares and pedicles) stress fractures and intervertebral disc degeneration in athletes whilst also allowing quantification of other, potentially associated factors such as paraspinal muscle asymmetry. However, there is very little published research regarding the use of modalities such as magnetic resonance imaging (MRI) in the identification and prognosis of these types of injuries in fast bowlers. Similarly, advances in three-dimensional (3D) motion analysis has aided technique evaluation in a variety of sports, however, little remains known about the pathomechanics of lower back injury in fast bowling. Therefore, the aim of this doctoral research was to investigate relationships between lower back injury and; the MRI appearance of the lumbar posterior bony elements and intervertebral discs, MRI-derived lumbar muscle morphology and the three-dimensional (3D) trunk kinematics of professional fast bowlers in cricket. This was examined in a series of five studies.

The first study undertaken was an investigation of the MRI appearance of the lumbar spines of 36 asymptomatic professional fast bowlers and 17 active controls. It was identified that the fast bowlers had a high prevalence of multi-level, predominantly non-dominant side, acute and chronic stress changes in the posterior bony elements of the lumbar spine. Multiple level disc degeneration was also more advanced in the fast bowlers compared with the control

participants. However, disc degeneration appeared not to be associated with lumbar stress injury.

The second study investigated the reliability and accuracy of using MRI to determine the FCSA of the lumbar paraspinal muscles (psoas, quadratus lumborum, erector spinae and multifidus). The novel methodology developed in this study was determined to be both valid and highly reliable. In the third study, this technique was then used to describe the functional cross-sectional area (FCSA) morphology of the paraspinal muscles in a group of 46 professional fast bowlers and the 17 control participants scanned in the first study. It reinforced that there was a higher prevalence of lumbar muscle asymmetry in the fast bowler group. Paraspinal muscle asymmetry, consistent with hypertrophy of the dominant side muscle, was most prevalent in the quadratus lumborum of fast bowlers, and was also evident in the lumbar multifidus in both groups of subjects.

The aims of the fourth study of the thesis were to quantify the proportion of lower trunk motion utilised during the delivery stride of fast bowling and to investigate the relationship between the most accepted fast bowling action classification system and potentially injurious kinematics of the lower trunk. 3D kinematic data were collected from 50 male professional fast bowlers during fast bowling trials and these were normalised to each bowler's standing lower trunk range of motion. A high percentage of the fast bowlers used a mixed bowling action attributable to having shoulder counter-rotation greater than 30°. The greatest proportion of lower trunk extension (26%), contralateral side-flexion (129%) and ipsilateral rotation (79%) was utilised during the front foot contact phase of the fast bowling delivery stride. There was no significant difference between mixed and non-mixed bowlers in the range of motion used during fast bowling. It was concluded that fast bowling action characteristics currently used to identify potentially dangerous action types may not be directly related to the likely pathomechanics of contralateral side lumbar stress injuries. It is proposed that coupled lower trunk extension,

ipsilateral rotation in addition to 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.

In the final study, a combination of the factors described in earlier studies i.e. the lumbar MRI appearance of the partes interarticulares and intervertebral discs, paraspinal muscle asymmetry and selected bowling action and delivery stride trunk kinematic variables, were examined. Therefore, the aim of this study was to examine the relationship between fast bowler lower back injury occurrence (one season either side of testing) and the aforementioned factors that were measured when participants were asymptomatic and bowling competitively.

The results of this study indicated that a high percentage of professional fast bowlers in the United Kingdom continue to sustain a high number of acute lumbar stress injuries and these result a significant amount of lost playing and training time. Fast bowling action classification and lower trunk kinematic variables were not conclusively linked to acute lumbar stress injury occurrence. However, further investigation of the effect of coupled lower trunk motion on non-dominant side lumbar bone stress is indicated.

The presence of acute MRI stress changes (particularly acute stress changes such as bone marrow oedema, periostitis and acute fracture lines) in the non-dominant side lumbar posterior elements seem to have a relationship with acute stress injury occurrence. Regular lumbar MRI scanning may assist in identifying early acute stress changes prior to the onset of symptoms. Intervertebral disc degeneration was less prevalent amongst professional fast bowlers who suffered acute stress injuries than those who had no significant lower back injury. Finally, although fast bowlers have a high prevalence of quadratus lumborum and lumbar multifidus asymmetry (larger on the dominant side), there was no observed relationship between acute lumbar stress injury and these findings.

## LIST OF PUBLICATIONS

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## **LIST OF ABBREVIATIONS**

3D	Three dimensional
BFC	Back foot contact
BFF	Back foot flat
BFI	Back foot impact
CSA	Cross-sectional area
CT	Computed tomography
FCSA	Functional cross-sectional area
FFC	Front foot contact
FFI	Front foot impact
FO	Front-on
LBP	Lower back pain
MR	Magnetic resonance
MRI	Magnetic resonance imaging
MW	Midway
ROM	Range of motion
SCR	Shoulder counter-rotation
SO	Side-on
SPECT	Single photon emission computed tomography
STIR	Short-inversion-time inversion recovery
US	Ultrasound

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## **CHAPTER 1 - Introduction**

Sections 1.1 to 1.6 of this chapter contain a review of relevant background literature. The first sections cite the epidemiology of lumbar injuries in fast bowlers and reviews the risk factors related to these conditions. Thereafter is a review of the structure and function of the lumbar paraspinal muscles and outlines their hypothesised role in lumbar injury. Following this is a discussion of the methods used to classify fast bowling actions and to quantify the kinematics of the lumbar spine during fast bowling. In the final part of the literature review, specific aspects of the use of magnetic resonance imaging (MRI) to evaluate spinal pathology and lumbar paraspinal muscle geometry are outlined.

The rationale and specific aims of the studies contained within the thesis are then detailed in Section 1.7 and the limitations of the studies are then stated in Section 1.8. Finally, a statement of the significance of the thesis is provided in Section 1.9.

## **1.1 The Epidemiology of Low Back Injury in Fast Bowlers in Cricket**

Athletes who participate in sports that involve repetitive flexion/extension, lateral flexion and/or rotation of the lumbar spine have been shown to have a higher incidence of low back pain (LBP) and spinal abnormalities compared with athletes in sports without these characteristics<sup>1-8</sup>. Spondylolysis (stress fracture of the pars interarticularis) and intervertebral disc degeneration of the lumbar spine are two of the most common pathological conditions identified in athletes participating in sports that place high demands on the lumbar spine<sup>4, 6, 8-11</sup>. Further, athletes in these sports clearly demonstrate a higher incidence of spondylolysis compared with the non-sporting population (3-6%)<sup>12</sup>. Sward<sup>7</sup> reported a much higher incidence of lumbar disc degeneration, defined as disc height reduction on conventional radiographs and reduced disc signal intensity on MRI, amongst wrestlers and gymnasts when compared with non-athletes.

Low back injury to fast bowlers is the biggest injury problem in the sport of cricket<sup>13, 14</sup>. In 1995 the Australian Cricket Board commenced a prospective injury surveillance programme of all senior State and National level cricketers. From this programme, the reported injury prevalence rates (percentage of squad members not available for selection due to injury for any given match) were approximately 3% for batsmen, compared with 16% for fast bowlers<sup>13, 15</sup>. Lumbar spine injuries are recognized as the injury category resulting in the greatest amount of missed playing time amongst Australia's State and National team fast bowlers. Of the specific diagnoses in this category, stress fractures of the partes interarticulares of L4 and L5 on the side contralateral to the bowling arm have by far the greatest prevalence<sup>13, 15</sup>. English County Cricket injury surveillance statistics report a slightly higher prevalence of fast bowler injury (18%), with low back injury, particularly lumbar stress fractures, again accounting for the most lost playing time<sup>16</sup>.



The first reports of high rates of low back injuries in fast bowlers began to appear in the scientific literature in the late 1980's. Foster *et al.*<sup>17</sup>, in a prospective study of back injuries in high performance adolescent bowlers, reported an 11% incidence of lumbar stress fracture in this group during one competitive season. A subsequent computed tomography (CT) study by Elliott *et al.*<sup>10</sup> of a similar group, found that 55% of participants were found to have abnormalities (pedicle sclerosis and pars stress fracture) in the posterior bony elements of the lumbar spine (pedicles and partes interarticulares) and 65% were identified as having evidence of lumbar disc abnormalities. Premature disc degeneration has been reported in as many as 21% of young bowlers with a mean age of 13.6 years<sup>18</sup> and 58% of bowlers with a mean age of 16.3 years<sup>9</sup>. Engstrom and colleagues<sup>19</sup> used MRI scanning to examine the lumbar spines of a cohort of 51 junior elite fast bowlers on an annual basis over a four-year period. The authors reported a 24% (12/51) incidence of symptomatic pars interarticularis stress injury development in this group during the period of the study. Furthermore, 92% of these injuries were reported to have occurred at the L4 level, exclusively on the side contralateral to the bowling arm. Other studies have reported that acute lumbar stress injuries in fast bowlers mostly occur at the L3 to L5 lumbar levels with most located on the non-dominant (non-bowling arm side) of the lumbar spine<sup>17, 20-22</sup>. The vast majority of lumbar spondylolyses (stress fractures) occur in the lower lumbar spine, with between 85% and 95% being reported to occur at the L5 spinal level and 5% to 15% at the L4 spinal level<sup>12</sup>.

Although no precise relationships between the degree of disc degeneration and incidence of LBP were reported in these investigations, evidence from this and other studies of the general population, would suggest that these pathological changes in the lumbar spine are likely to increase the risk of clinically significant LBP<sup>23, 24</sup>.

There is however, some debate in the wider LBP literature regarding the relationship between LBP and radiological abnormalities and biomechanical factors<sup>25, 26</sup>. This debate has

arisen previously as MRI studies examining asymptomatic participants have demonstrated a high prevalence of disc degeneration and derangement<sup>27,28</sup>. Further, other investigations have found that genetic predisposition<sup>24,29-31</sup> has a greater influence on lumbar patho-anatomical findings than physical factors. In addition, psycho-social factors such as stress levels, job satisfaction and the work environment correlate more closely with the incidence of LBP than either radiological findings or biomechanical influences<sup>32-34</sup>. Conversely, MRI investigations conducted by MacGregor and colleagues<sup>24</sup> and Luoma and co-workers<sup>23</sup> have found that the degree of disc degeneration was a strong predictor of a history of severe LBP. Similarly, Kjaer and colleagues<sup>35</sup> reported most MRI degenerative disc abnormalities e.g. irregular nucleus shape, reduced disc height, hypointense disc signal, annular tears, disc protrusions and endplate changes, to be moderately associated with LBP.

### ***Key Points***

- Low back injury in fast bowlers is the most important injury problem in the game of cricket.
- Stress injuries of the lumbar posterior elements (pedicles and partes interarticales) in fast bowlers results in the most loss of playing time in cricket.
- Most lower back stress injuries in fast bowlers are located in the posterior bony elements (partes interarticales and pedicles) of the non-dominant side L3 to L5 lumbar levels.
- Junior elite fast bowlers have high rates of premature intervertebral disc degeneration.
- There is evidence to suggest that mechanical loading is related to LBP in sport. There are several sports that show rates of LBP higher than that displayed in the normal population. These sports tend to involve repetitive flexion/extension, lateral bending and axial rotation of the spine that is at, or near end-range.

- Most lower back stress injuries in fast bowlers are located in the posterior bony elements (partes interarticulares and pedicles) of the non-dominant side L3 to L5 lumbar levels.
- Although debate exists, evidence supports a relationship between abnormal radiological findings and symptoms of LBP.

## **1.2 Risk Factors for Low Back Injury in Fast Bowlers**

The aetiology of LBP in the general population is thought to be multi-factorial. There is a large body of literature describing relationships between LBP and various combinations of entities that include; workload <sup>17, 36, 37</sup>, physical characteristics <sup>17</sup>, spinal radiological abnormalities <sup>23, 24</sup>, abnormal movement patterns <sup>38</sup>, muscle imbalances <sup>39</sup>, altered neuromuscular control <sup>40-42</sup>, previous history of LBP <sup>42-44</sup> and psycho-social issues <sup>45, 46</sup>. Some of these factors have been examined during previous investigations of low back injury in fast bowlers.

Overuse has been implicated in the development of lumbar injury amongst elite fast bowlers, and there is increasing evidence to support this theory <sup>17, 36, 47</sup>. Foster and co-workers <sup>17</sup>, in a prospective study of low back injuries in high performance young fast bowlers, reported that 59% of bowlers (as opposed to 38% for the entire group), who bowled in greater than the mean number of matches, suffered a low back injury. More recently, Dennis and colleagues <sup>36</sup> conducted a study of the workload of elite senior Australian Fast bowlers in which they reported that bowlers who averaged less than two days between bowling sessions, or bowled more than an average of 188 deliveries per week, were at significantly increased risk of injury than bowlers who bowled less deliveries or less frequently.

Several studies, elaborated upon in Section 1.4, have associated the use of a particular bowling action type, the mixed action, with the high incidence of low back injury and radiological abnormalities amongst fast bowlers <sup>9, 10, 17, 18, 48, 49</sup>. Other aspects of bowling

technique that have been associated with an increased risk of low back injury include; i) having an extended front knee position during the front foot contact (FFC) phase of the delivery stride<sup>17, 49</sup> and ii) having a faster ball release speed<sup>20</sup>. These two factors would appear to be directly related as faster bowlers tend to have a relatively extended front knee at FFC<sup>50</sup>. This is thought to allow more efficient kinetic energy transfer to the ball, as the body rotates over a ‘braced’ front leg<sup>49</sup>. The probable injurious consequence of this mechanism is that having an extended, or extending, front knee at FFC reduces the bowler’s ability to attenuate impact forces, placing greater stress on the skeletal structures of the lower body and spine<sup>51</sup>.

A recent prospective study reported a strong association between asymmetry of a paraspinal muscle, quadratus lumborum, and an increased incidence of pars interarticularis stress injuries in a group of elite junior fast bowlers<sup>52</sup>. The relationship between paraspinal muscle asymmetry and LBP will be discussed further in Section 1.5.

### ***Key Points***

- The aetiology of LBP within the general population is thought to be multifactorial.
- Risk factors that have previously been associated with low back injury in fast bowlers in cricket have included; workload, high bowling velocity, paraspinal muscle asymmetry and having an extended or extending front knee during the delivery stride.

## **1.3 The Link between Fast Bowling Technique and Lumbar Injury**

There exists a broad continuum of fast bowling action types ranging from a pure side-on action to a pure front-on action. A pure side-on action is characterised by the bowler’s pelvis and shoulders being aligned down the wicket at back foot contact (BFC) with minimal counter-rotation of the shoulders during the delivery stride. A pure front-on action is characterized by the

bowler's pelvis and shoulders being aligned across the wicket at BFC, again with minimal counter-rotation of shoulders through the delivery stride<sup>51</sup> (Figure 1.1).

The classification of various action types within this continuum has developed considerably over the past two decades. A mixed action, where there is excessive counter-rotation of the shoulders (SCR) to a more side-on position after BFC (Figure 1.2), was originally described by Foster and colleagues<sup>17</sup> who associated this action type with a greater likelihood of the bowler sustaining low back injury. Researchers who have measured pelvic and shoulder alignment during the delivery stride of the fast bowling action using three-dimensional (3D) motion analysis systems, have also classified bowlers with a pelvis to shoulder separation angle of greater than 30° at BFC as having a mixed action<sup>49, 53, 54</sup>. However, there has not been a consensus on what exactly constitutes a side-on, front-on or mixed action<sup>9, 10, 18, 51</sup>.

Currently, the most commonly accepted classification system for fast bowling technique is that cited by Portus and colleagues<sup>49</sup> with the criteria for each action type being:

**Side-on:** a shoulder angle of less than 210° to the right hand horizontal at BFC, a pelvis to shoulder separation angle of less than 30° at BFC, and, SCR of less than 30° between BFC and front foot contact (FFC).

**Midway:** a shoulder angle from 210 to 240° at BFC, a pelvis to shoulder separation angle of less than 30° at BFC, and SCR of less than 30°.

**Front-on:** a shoulder angle of greater than 240° at BFC, a pelvis to shoulder separation angle less than 30° at BFC, and SCR less than 30°.

**Mixed:** a pelvis to shoulder separation angle of 30° or more at BFC, or, SCR of greater than 30°.

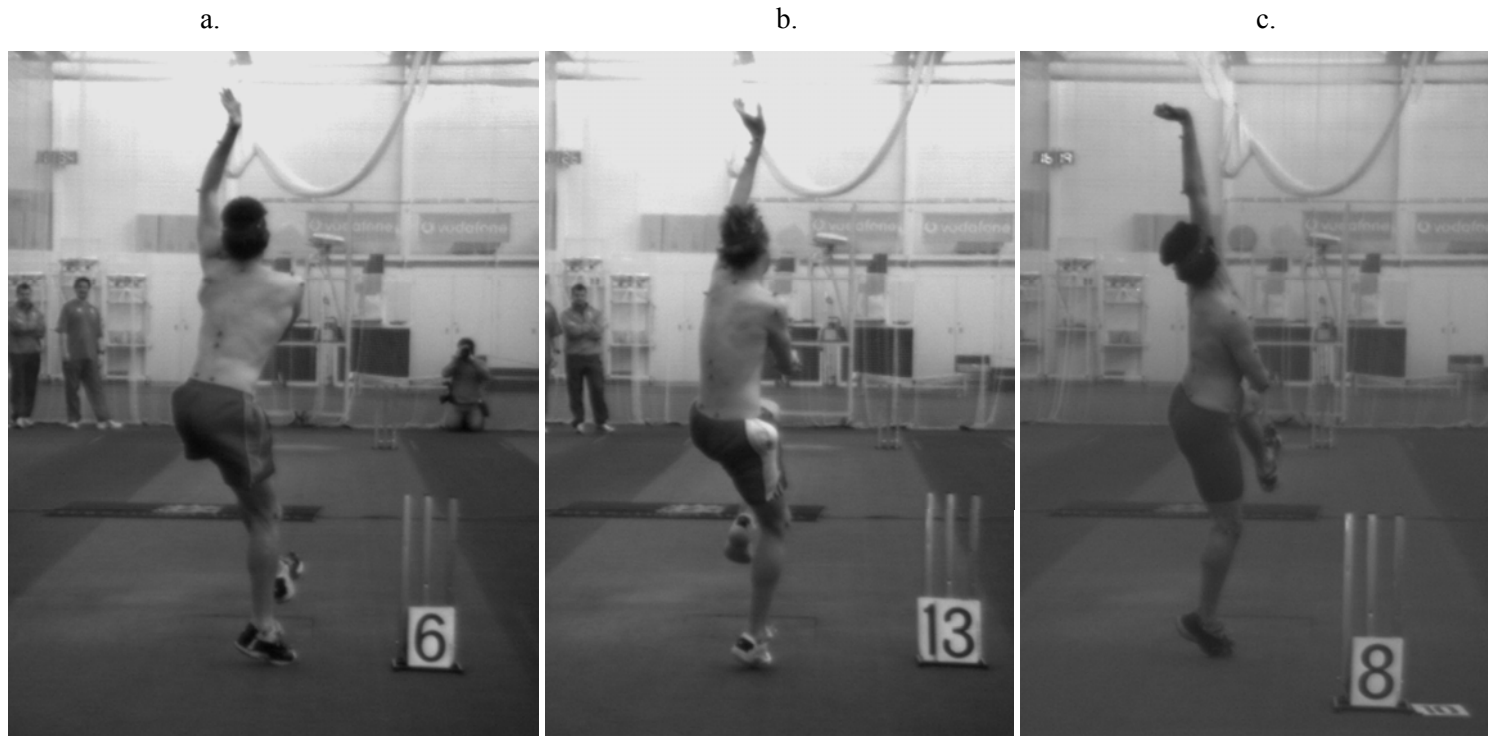


Figure 1.1 a) Front on, b) midway and c) side-on shoulder alignment at back foot contact.

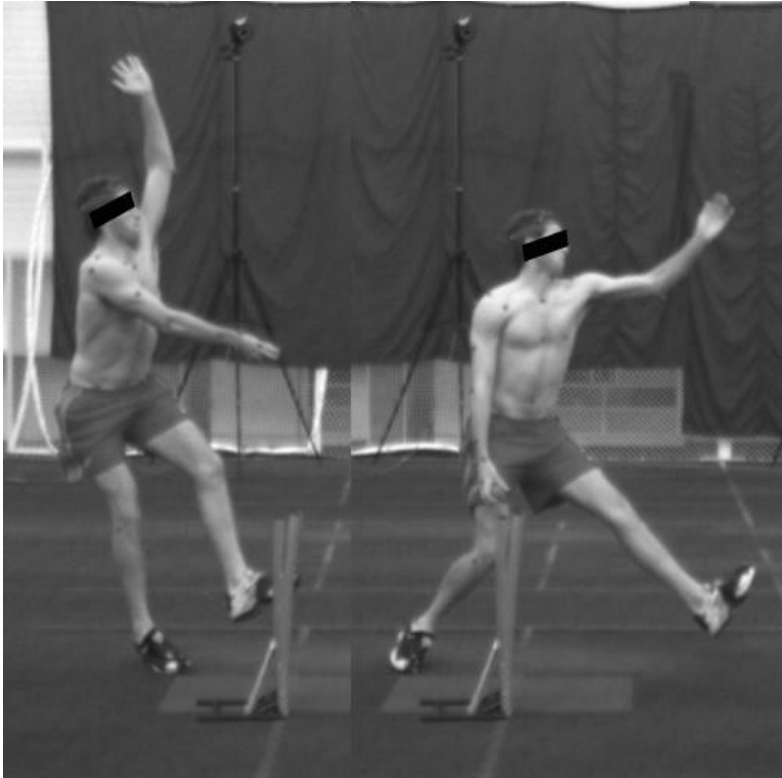


Figure 1.2 Shoulder Counter-Rotation from a front-on alignment at back foot contact, to a relatively side-on alignment prior to front foot contact.

The precise mechanism behind the mixed action's association with elevated rates of lumbar spine injury is currently unknown. However, several authors have proposed that greater amounts of pelvis to shoulder separation and SCR during the delivery stride, increases the amount of torsional stress placed upon the lumbar spine, predisposing low back injury<sup>9, 10, 17, 18, 55</sup>.

In addition, Burnett and colleagues<sup>56</sup> reported that compared with non-mixed action bowlers, bowlers who displayed a mixed action displayed a greater magnitude and velocity of movement of the lumbar spine during the delivery stride of the bowling action. Specifically, mixed action bowlers demonstrated greater lumbar extension, greater lateral bend to the side contralateral to the bowling arm at front foot contact (FFC), and a greater range of motion and angular velocity of the trunk in the lateral bending and flexion/extension axes.

Portus and colleagues<sup>49</sup> identified a strong positive relationship between the mixed action and the incidence of lumbar injury in bowlers. The authors also postulated that the type of mixed technique that most predisposed the development of lumbar stress fractures was one where the bowler has relatively aligned pelvis and shoulder segments at BFC (as for a front-on action) but this was followed by excessive counter-rotation of the shoulders (SCR) to a more side-on position prior to FFC.

However, SCR, the variable most commonly used to define the mixed action, is a significantly removed derivative of trunk rotation<sup>56, 57</sup> and mechanical modelling studies investigating injury mechanisms in the lumbar spine have indicated that torsional stresses alone are unlikely to be the major pathomechanical factor in lumbar stress injury<sup>58</sup>. Chosa and co-workers<sup>58</sup> found that unilateral pars interarticularis stress was greatest under combinations of compression with lumbar extension, compression with lumbar side flexion to the same (ipsilateral) side, and, compression with lumbar rotation to the opposite (contralateral) side. Further, it is known that the available range of motion (ROM) of lumbar axial rotation is reduced



when the spine is in extended positions <sup>59, 60</sup>, therefore implying increased stiffening, and hence, risk of tissue strain of the spine when performing coupled movements near the limits of its physiological ROM. Panjabi <sup>61</sup> termed this zone of high stiffness towards end range the “elastic zone of motion”.

*In vitro* studies have reported that increasing the amounts of compression, torsion, lateral bending, flexion and extension of the lumbar spine eventually leads to injury of the lumbar discs <sup>62, 63</sup>. In addition, repeated lumbar extension combined with rotation has been cited as the probable mechanical aetiology of posterior element stress fracture in athletes <sup>12</sup>. Lumbar spine movement nearing the end range of motion, combined with ground reaction forces of up to five times a bowler’s body mass during delivery <sup>10, 12, 17, 18, 64, 65</sup> is likely to place excessive stress on the lumbar spine of mixed action bowlers. These factors are likely to be major aetiological factors in the high rate of lumbar injury and radiological abnormality seen amongst fast bowlers.

### ***Key Points***

- Fast bowling actions can be classified into one of four types; front-on, midway, side-on and mixed.
- Previous research has repeatedly reported an association between the use of the mixed action type and the occurrence of low back injury.
- The pathomechanical relationship between the use of a mixed action type and low back injury is not well understood.

#### **1.4 Asymmetry of the Lumbar Paraspinal Muscles - A Risk Factor in Low Back Injuries in Fast Bowling?**

There is increasing evidence that the primary function of the lumbar paraspinal muscles is to provide segmental stabilisation of the lumbar spine via their direct attachments to the lumbar spinal column<sup>40, 41</sup>. Muscles in this group consist of the psoas, quadratus lumborum and the lumbar parts of iliocostalis and longissimus and, the lumbar multifidus (see Table 1.1 for anatomical detail of these muscles). Coordinated, co-contraction of the paraspinal muscles in conjunction with the abdominal wall, diaphragm and pelvic floor musculature is thought to have a stabilizing effect on the lumbar spine thus providing a safe platform for the larger dynamic trunk muscles to act upon<sup>38, 40, 66</sup>.

Recent studies have linked asymmetry in the size of the lumbar paraspinal muscles with both injury, and recurrent injury. Unisegmental atrophy of the lumbar multifidus<sup>44, 67, 68</sup> and psoas major muscles<sup>69</sup>, ipsilateral to the painful side, has been demonstrated amongst members of the general population suffering LBP and injury. Localised atrophy of the lumbar multifidus does not recover spontaneously following resolution of LBP and it is thought to be a sequelae to pain-induced inhibition of this muscle<sup>44, 70</sup>. Hence, a resultant deficit in the segmental stabilising capacity of the spine is a proposed mechanism for recurrent low back injury<sup>44, 68</sup>. It should be noted however, that the cross-sectional area of the muscles in these studies was measured only after the onset of pain using ultrasound imaging. It is therefore possible that the muscle asymmetry was pre-existing and may have been a predisposing factor for the onset of LBP, possibly via a mechanism of reduced stabilising capacity of the spinal segment adjacent to the atrophied muscle.

Table 1.1 The attachments, orientation and functions of the paraspinal muscles; psoas, quadratus lumborum, iliocostalis lumborum, lumbar longissimus and the lumbar multifidus.

Muscle	Attachments and Orientation	Functions
Psoas	Arises from the lower border of the T12 vertebra down to the upper border of the L5 vertebral body and the lateral border of the intervening intervertebral discs. Narrows it passes anterior to the pelvis and joint the iliacus to insert into the lesser trochanter of the femur <sup>71</sup> .	Flexion of the hip Eccentric control of extension and contralateral side flexion of the lower trunk <sup>71</sup>
Quadratus Lumborum	Originates via an aponeurosis from the iliolumbar ligament and the adjacent 5cm of the iliac crest.  Fibres run supero-medially to insert into the lower border of the 12 <sup>th</sup> rib, and by four tendon slips onto the tips of the transverse processes of L1 to L4 <sup>72</sup> .	Segmental stabilisation of lumbar spine, primarily during side flexion <sup>66, 73, 74</sup> .  If the thorax and vertebral column are fixed, it may unilaterally raise the pelvis <sup>72</sup> .  Acts unilaterally as a strong lumbar side-flexor.  Assists lumbar extension when acting bilaterally.  Draws down the last rib, and acts as a muscle of inspiration by helping to fix the origin of the diaphragm.
Iliocostalis Lumborum	Originates from the ilium and the erector spinae aponeurosis and attaches to the lateral part of the transverse processes of the lumbar vertebrae and the adjacent thoracolumbar fascia <sup>75</sup>	Trunk extension Trunk side-flexion to the same side
Lumbar Longissimus	Originates from the accessory processes and the medial part of the transverse processes of the lumbar vertebrae. Fascicles from L1-L3 attach to the erector spinae aponeurosis. Fascicles from L4 & L5 insert into the medial iliac crest and PSIS. <sup>75</sup> .	Trunk extension and eccentric control of trunk flexion Trunk side-flexion to the same side
Lumbar Multifidus	Most medial of the major low back muscles.  Each lumbar multifidus muscle (L1-5) has five fascicles.  The fascicles spread infero-laterally from a common point of origin on each of the lumbar vertebral spinous processes.  For the L1 lumbar multifidus, the most medial fascicle inserts onto the mammillary process of L3 with the successive bands lateral to that inserting onto the mammillary process of L4, L5, S1 and the posterior superior iliac spine. A similar pattern of attachment occurs with the multifidii of the other lumbar levels.  A modification of the lower lumbar multifidii is that they have insertions onto the dorsum of the sacrum and sacro-iliac ligament, as there are no mammillary processes on the sacrum. <sup>76</sup> .	Arthrokinetic control of the lumbar vertebral segments <sup>77</sup>  Stiffening of the intervertebral discs <sup>78</sup>  Extension and eccentric control of lower trunk flexion

A recent prospective study conducted using a group of elite junior fast bowlers reported a strong association between asymmetry of quadratus lumborum muscle volume and an increased incidence of stress injuries of the contralateral L4 pars interarticularis<sup>52</sup>. The authors inferred that asymmetry of the quadratus lumborum muscle placed greater shear loading on the contralateral L4 pars interarticularis, predisposing it to stress injury. However, as the quadratus lumborum asymmetry was present prior to the injuries occurring, it could be argued that characteristics of the bowling action that resulted in hypertrophy of the dominant side quadratus lumborum, also resulted in high stress in the contralateral pars interarticularis that eventually led to stress fracture. Similarly, de Visser and co-workers<sup>79</sup> when reporting on a mechanical modelling study proposed that hypertrophy of the dominant side quadratus lumborum may be due to an adaptive mechanism, albeit ineffective in some cases, possibly aimed at reducing stress in the contralateral lumbar spine.

Raty and colleagues<sup>80</sup> used MRI to measure the cross-sectional area (CSA) of the lumbar muscles of former elite athletes at the L3/4 spinal level. The authors found the CSA of the quadratus lumborum muscle to be slightly larger in soccer players compared with weight lifters, distance runners and shooters<sup>80</sup>. Of these four groups of athletes, it is the soccer players who perform the most dynamic, multidirectional trunk and limb movements. This finding may support the suggestion that the stabilising function of quadratus lumborum causes it to hypertrophy in an asymmetrical manner in some fast bowlers<sup>52</sup>. This is because the fast bowling delivery stride also involves repeated, dynamic, multidirectional trunk and limb movements including extreme contralateral side lumbar side-flexion that is likely to require high levels of stabilising, eccentric and isometric activation of the quadratus lumborum muscle<sup>74</sup>.

An alternative explanation for the quadratus lumborum volume asymmetry observed by Engstrom *et al.*<sup>52</sup> is segmental atrophy of the contralateral side muscle. The partes interarticulares stress injuries that were found to be associated with this type of muscle

asymmetry, mostly occurred at one spinal level, L4, on the same side as the smaller quadratus lumborum muscle volume<sup>81</sup>. As discussed at the beginning of this section, other lumbar paraspinal muscles, namely multifidus and psoas, have been shown to be unisegmentally atrophied, on the painful side, at the painful level, in members of the general population with LBP<sup>67,69</sup>. Therefore, a similar pattern of unisegmental atrophy of the quadratus lumborum muscle may have contributed to the asymmetry described by Engstrom *et al.*<sup>52</sup>. It may also have contributed to the causation of the partes interarticulares stress injuries that were associated with quadratus lumborum asymmetry i.e. via a reduction of the stabilising capacity of the adjacent spinal segment.

Unfortunately, the abovementioned hypotheses remain speculative as there is currently no published data pertaining to the segmental morphology and symmetry of the lumbar paraspinal muscles in elite senior fast bowlers. This is despite a very high rate of low back injury in this population. There is some data available regarding the morphology of the lumbar paraspinal muscles from both cadaveric and *in-vivo* MRI studies<sup>82,83</sup>. However, this information is probably not appropriate for developing accurate biomechanical models of stress on the lumbar spine in specific athletic populations such as fast bowlers, who are likely to have very different muscular development to the participants in those previous studies<sup>79,84</sup>. Establishing the morphological characteristics of the paraspinal muscle asymmetry amongst fast bowlers is necessary for investigations of a possible relationship between paraspinal muscle asymmetry and the high rate of low back injury and radiological abnormalities in fast bowlers in cricket.

### ***Key Points***

- The primary function of the lumbar paraspinal muscles is to control and initiate movements of the lower trunk in conjunction with the abdominal wall and thoracic muscles

- Asymmetry of the multifidus and psoas muscles has been associated with LBP in the general population.
- Asymmetry of the quadratus lumborum has been associated with lumbar stress fracture in elite junior fast bowlers in cricket however the nature of this association has not been elucidated.
- There is currently no published data pertaining to the morphology of the paraspinal muscles in fast bowlers in cricket. This information is important for:
  - Accurate biomechanical modelling of the effect of paraspinal muscle asymmetry on lumbar spine stress
  - Determining if a relationship exists between paraspinal muscle asymmetry and the high rate of low back injury and radiological abnormalities in fast bowlers in cricket

## **1.5 Methods Used in the Kinematic Analysis of Fast Bowling Technique and Low Back Movement**

Methods used to classify fast bowling technique have relied exclusively upon two-dimensional (2D) <sup>10, 17, 48, 85</sup> and three-dimensional (3D) motion analysis techniques <sup>54-56, 86</sup>. 2D video footage generated from a camera positioned above the bowler during the delivery stride allows the shoulder angle and the degree of SCR during the delivery stride to be measured. Elliott and colleagues <sup>87</sup> reported that 2D shoulder alignment accurately reflects the degree of trunk rotation early in the delivery stride but not after FFC when the shoulders move out of the plane of the overhead camera. This is an important limitation of 2D action classification methods as it is possible that the greatest stresses on the lumbar spine actually occur after FFC <sup>56</sup>.

3D cinematography allows the alignment of the pelvis and shoulders (shoulder angle and pelvis-shoulder separation angle) to be measured <sup>55, 57</sup>. Typically, 3D techniques involve participants being filmed by two or more high-speed cameras, operating at between 50 to 250Hz. Retro-reflective markers indicating body segment position can be tracked and subsequently processed using motion analysis software.

The accurate measurement of spinal motion is vital to advancing the understanding of the pathomechanics of lumbar injuries, such as those that occur in fast bowlers in cricket. Over the last few decades a variety of methods pertaining to the accurate and reliable measurement of lumbar kinematics have been presented in the scientific literature. These include tracking the 3D motion of wires and pins implanted in the spine <sup>88</sup>, biplanar radiography <sup>89</sup>, video fluoroscopy <sup>90</sup>, and simple goniometry and inclinometry <sup>91</sup>. For a variety of ethical and practical reasons none of these methods are suitable for analysis of dynamic sporting activities such as the delivery stride during fast bowling.

Image based motion analysis methods such as the VICON motion analysis system (ViconPeak, Oxford, UK) and electromagnetic devices such as 3-Space<sup>®</sup> Fastrak<sup>™</sup> (Polhemus Navigation Sciences Division, Vermont, USA) are logistically the best methods to quantify the kinematics of the lumbar spine during such a complex and dynamic manoeuvre as delivering a cricket ball. Specifically, these methods have the ability to track and measure complex, high velocity movements of body segments during activities such as fast bowling <sup>56, 87, 92, 93</sup>.

### ***Key Points***

- Fast bowling techniques can be simply classified using 2-D video to calculate shoulder alignment during the delivery stride of fast bowling.

- 2D measurement of shoulder alignment may not accurately reflect trunk position, especially late in the delivery stride as the shoulders move out of the plane of the camera.
- 3D motion analysis techniques are currently considered the ‘gold standard’ for use in classifying fast bowling action.
- 3D electromagnetic and opto-electric motion analysis systems allow kinematics analysis of complex sporting activities such as fast bowling and each system has its unique advantages and disadvantages.

## **1.6 Magnetic Resonance Imaging (MRI) of the Lumbar Spine**

### *1.6.1 Evaluation of lumbar spine abnormality using MRI*

Improvements in MRI technology that allows the production of high resolution images of lumbar spinal anatomy and pathology, provides MRI with many advantages over other radiological techniques such as radiographs, computerised tomography (CT) and bone scintigraphy<sup>94,95</sup>. MRI does not expose participants to ionizing radiation, or radiographic isotopes, and has been shown to be at least as sensitive as other imaging techniques to a wide variety of diagnoses including marrow oedema in the lumbar posterior elements (partes interarticulars and pedicles), lumbar spondylolysis, spondylolysthesis, disc degeneration and foraminal narrowing<sup>96,97</sup>.

MRI has previously been employed as the radiological technique of choice to identify and classify bony and disc abnormalities that occur in the lumbar spines of fast bowlers in cricket<sup>9,19</sup>. MRI may also play an increasing role in identifying the early signs of lumbar posterior element stress injury via a new MRI classification system for these injuries<sup>97</sup>.



Hollenburg *et al.*<sup>96</sup> classified the MRI appearance of stress reactions of the lumbar posterior elements into one of five grades (Table 1.2) and this system has found to be reliable.

Table 1.2 MRI classification of stress reactions of the lumbar posterior elements. Adapted from Hollenburg *et al.* (2002).

Grade	MRI Appearance of the Lumbar Posterior Elements
0	No signal abnormality.
I	T2 signal abnormality, no signal changes in adjacent pedicle or articular process.
II	T2 abnormalities + pars thinning, fragmentation or irregularity on T1 or T2 weighted images.
III	T2 signal + complete unilateral or bilateral spondylolysis.
IV	Complete spondylolysis without abnormal T2 signal (old united pars fractures).

Table 1.3 MRI classification of lumbar intervertebral disc degeneration. Adapted from Pfirrmann *et al.* (2001).

Grade	Structure	Distinction of Nucleus and Annulus	Signal Intensity	Height of Intervertebral Disc
I	Homogenous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
II	Inhomogeneous, with or without horizontal bands	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
III	Inhomogeneous, gray	Unclear	Intermediate	Normal to slightly decreased
IV	Inhomogeneous, gray to black	Lost	Intermediate to hypointense	Normal to moderately decreased
V	Inhomogeneous, black	Lost	Hypointense	Collapsed disc space

Pfirrmann and colleagues<sup>98</sup> evaluated a morphologic grading system relating to pathologic changes in lumbar discs as seen on MRI. The grading system shown in Table 1.3 is a 5-point scale (I-V) based on MRI signal intensity, disc structure, the distinction between nucleus and annulus, and disc height. Good intra- and inter-observer agreement was found with assessment of over 300 lumbar intervertebral discs and the grading system was therefore declared a standardised and reliable assessment tool for describing lumbar disc pathology.

#### 1.6.2 *Quantification of trunk muscle morphology using MRI*

As outlined in Section 1.4, alterations in the size and symmetry of the paraspinal muscles have been associated with the occurrence of LBP. Muscle CSA is also considered as being an important factor in determining the maximum force a muscle can generate<sup>82, 84</sup>. Imaging techniques such as ultrasound<sup>99</sup>, computed tomography (CT)<sup>68</sup> and MRI<sup>80, 82, 83, 99-101</sup> allow *in-vivo* calculation of low back muscle CSAs. Of these three modalities MRI has advantages as it provides excellent differentiation between muscle, bone and connective tissue<sup>83, 94, 99</sup> without exposure to ionising radiation.

Investigations into the aetiology of LBP<sup>102, 103</sup> and neck pain<sup>104</sup>, have revealed that significant atrophy of specific lumbar paraspinal muscles can occur without a reduction in the total CSA within the muscles' fascial boundaries. These authors described paraspinal muscle atrophy in terms of replacement of muscle with fat and fibrous tissue, which would result in reduced functional contractility of muscle. Therefore, a measure of the functional cross-sectional area (FCSA) i.e. the area of lean muscle tissue within a muscle's fascial boundaries would be a better indicator of the muscle's contractile ability.

Segmentation (or tissue classification) is the process whereby various tissues visible on either a CT or MRI image are distinguishable by the signal intensity they emit<sup>105-110</sup>. Danneels *et al.*<sup>68</sup> conducted a study that used CT in conjunction with image processing software to produce quantitative measurement of “low-fat” CSA's of low back muscles. Their approach involved

eliminating pixels within the fascial boundary with grey scale values that were thought to represent fat. In the Daneels and co-workers' study however, the method of determining grey scale values for the different tissue types was not described in detail.

Although previous investigators have used MRI signal intensity to segment tissue types including fat, bone and muscle<sup>111, 112</sup> it remains a complex area in automated MRI analysis<sup>105, 106, 108, 110, 113, 114</sup>. A variety of biological and measurement effects on MRI signal intensity<sup>105, 106, 115</sup> which poses significant problems for researchers wishing to measure the FCSA of the paraspinal muscles. As a consequence most previous MRI studies have relied upon radiologist assessment and grading of the muscles' appearance i.e. degree of muscle atrophy and fat infiltration, without quantitative assessment of the intramuscular morphology<sup>102, 103</sup>.

### ***Key Points***

- MRI scanning allows reliable classification and quantification of lumbar intervertebral disc and bony stress injuries without the disadvantage of exposure to ionising radiation associated with other radiological modalities.
- Measurement of lumbar paraspinal muscle CSA can be undertaken using MRI and image processing software.
- Most previous studies have only measured raw CSA or used qualitative estimates of paraspinal muscle morphology.
- Muscle CSA may not give an accurate indication of the contractile ability of the paraspinal muscles as intramuscular atrophy with associated fat and fibrous tissue infiltration may maintain CSA but significantly reduced functional CSA (FCSA).

## 1.7 Objectives of the Thesis

The overall hypothesis of the thesis is that fast bowlers in cricket suffer a unique pattern of lumbar stress injury that is directly related to firstly, previously unidentified lumbar spine kinematics during the bowling action and secondly, characteristics of their lumbar paraspinal muscle morphology (Figure 1.3).

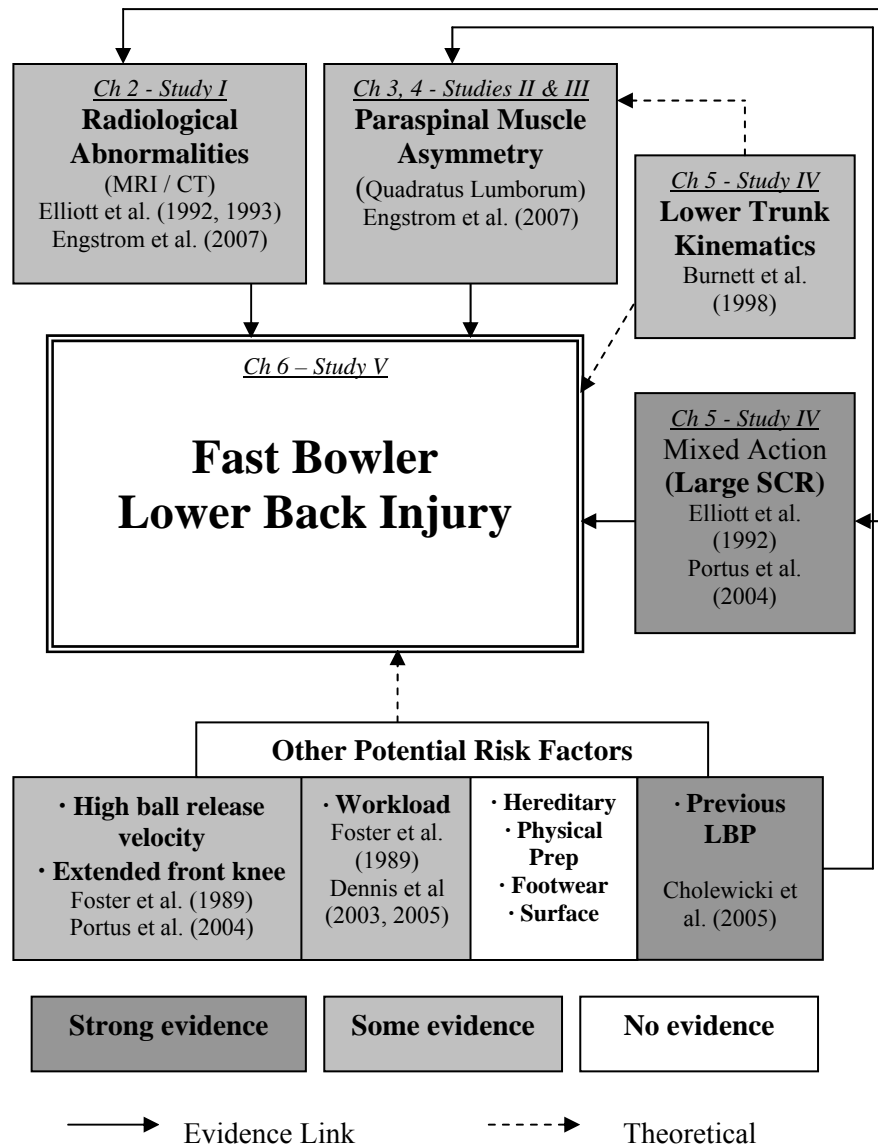


Figure 1.3 A schematic representation of the how the studies (Studies I-V as shown in Chapters 2-6) of the thesis link with the current evidence base and the aims of the research.

The objectives of this thesis (and the specific studies related to them) were as follows:

**Chapter 2 - Study I.** MRI findings of the lumbar spine in asymptomatic professional Fast bowlers in cricket.

To characterise the bony and intervertebral disc abnormalities of the lumbar spine in asymptomatic professional fast bowlers and a control group.

**Chapter 3 - Study II.** An investigation into the use of MRI to determine the functional cross sectional area of lumbar paraspinal muscles.

To develop a valid and reliable method of quantifying the *in-vivo* functional cross-sectional area of the lumbar paraspinal muscles using MRI.

**Chapter 4 - Study III.** The lumbar paraspinal muscle morphometry of fast bowlers in cricket.

To describe the morphology of the lumbar paraspinal muscles in asymptomatic professional fast bowlers compared with a control group.

**Chapter 5 - Study IV.** The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket.

To determine the relationship between the current method of fast bowling action classification and the likely pathomechanics of the unique pattern of low back injuries suffered by fast bowlers.

**Chapter 6 - Study V.** Relationships between acute lumbar stress injury, trunk kinematics, lumbar MRI and paraspinal muscle morphology in fast bowlers in cricket.

To investigate relationships between fast bowling technique (including lumbar spine kinematics), MRI findings, lumbar paraspinal muscle morphology and low back injury, particularly acute lumbar stress injury (stress reaction and stress fracture) occurrence.

## **1.8 Limitations of the Project**

The world population of professional fast bowlers in cricket is small and spread over a large geographical area. This makes it very difficult to carry out prospective longitudinal studies of injured participants of sufficient power. Therefore, testing for this research involved only asymptomatic participants which limits the inferences that can be made to the low back injury process in this population. Another factor that limits the generalisability of the research is that professional fast bowlers in cricket are a relatively homogenous population and the aetiology of the lower back injuries they suffer is likely to be unique to their occupation.

Significant technological advances in 3D motion analysis now make it possible to directly measure lumbar spine motion during fast bowling. However, this process continues to rely on tracking skin markers which give gross estimations of trunk kinematics. As this technology evolves it may become possible to accurately calculate segmental lumbar motion during fast bowling, information that is ultimately required to precisely describe the pathomechanics of lumbar stress injury.

## **1.9 Significance of the Thesis**

Despite research efforts since the 1980s there remains limited knowledge of the risk factors that contribute to the high prevalence of low back injuries in fast bowling. The specific nature of lumbar stress injuries in fast bowlers and the associated pathomechanics are poorly understood. This is the first series of studies to investigate the association between the morphology and patho-anatomy of the lumbar spine, and, lumbar kinematics during fast bowling in a large cohort of professional fast bowlers. This research will lead to advances in the diagnosis, prevention and rehabilitation of lumbar stress injuries in cricket and possibly other sports.

## 1.10 References

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## **CHAPTER 2 - Study I**

Low back injuries are epidemic amongst professional fast bowlers in cricket and various medical imaging modalities are commonly used in their clinical evaluation. There are very few studies that have examined the radiological appearance of the lumbar spine in fast bowlers in cricket and none that have investigated a large group of professional fast bowlers. Burnett and colleagues (1996) and Elliott and colleagues (2002) found a greater prevalence of lumbar intervertebral disc degeneration, as seen on MRI, in young fast bowlers who used a certain bowling action type. Gregory and co-workers (2004) performed a retrospective investigation of the radiological assessments (X-ray, CT and SPECT) of athletes with the diagnosis of spondylolysis and found that the cricketers amongst the cohort suffered mainly non-dominant side stress fractures.

SPECT and reverse gantry CT are the current 'gold standard' modalities for imaging the posterior bony elements of the lumbar spine. MR imaging has several advantages over these modalities as; it does not involve exposure to ionising radiation, it allows superior recognition of acute bony stress changes and improved visualisation of soft tissue structures e.g. lumbar ligaments and muscles. The significance of this original study is that it may facilitate the development of MR imaging in the investigation of low back pain in athletes. This may reduce the reliance on potentially hazardous imaging modalities that are the current 'gold standard'.

The general aims of this study were to classify the MRI appearance of the lumbar intervertebral discs and posterior bony elements (partes interarticulares and pedicles) of professional fast bowlers in cricket and a group of active controls. An additional aim was to investigate the reliability of the classification systems employed.

## **Magnetic Resonance Imaging findings of the lumbar spine in asymptomatic professional fast bowlers in cricket.**

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Ranson C, Kerslake R, Burnett A, Batt M and Abdi, S. Magnetic resonance imaging of the lumbar spine of asymptomatic professional fast bowlers in cricket. *Journal of Bone and Joint Surgery [Br]*. 87-B:1111-1116, 2005.

### **2.1 Abstract**

Previous radiological studies have reported a high prevalence of lumbar disc degeneration and partes interarticulares stress injuries in elite junior fast bowlers. The aim of this study was to compare the magnetic resonance imaging (MRI) appearance of the lumbar spines of professional fast bowlers and active control participants. The results indicate that fast bowlers have a relatively high prevalence of multi-level lumbar disc degeneration and a unique pattern of non-dominant side stress lesions of the lumbar posterior elements. The systems used to classify the MRI appearance of the lumbar discs and posterior elements were found to be reliable. However, the relationship between radiological findings, pain and dysfunction remains unclear.

## 2.2 Introduction

Injury surveillance programmes instigated by the governing bodies of professional cricket in Australia and the United Kingdom have revealed that low back injuries are epidemic amongst fast bowlers<sup>1-3</sup>. The specific diagnoses that result in the most lost playing time for professional fast bowlers are lumbar stress injuries such as spondylolysis and spondylolysthesis<sup>3</sup>.

Lumbar intervertebral disc degeneration has also been shown to be highly prevalent amongst junior elite fast bowlers<sup>4-6</sup>. Elliott et al.<sup>6</sup> found in a group of fast bowlers (mean age 17.9 years) that 65% of these players displayed at least one abnormal disc. In addition, Burnett *et al.*<sup>4</sup> undertook a magnetic resonance imaging (MRI) follow-up study where 21% of a group of 13 to 14 year-old fast bowlers displayed at least one intervertebral disc abnormality. When this same group was scanned 2.5 years later the prevalence of disc abnormality had increased to 58%. A loss of normal intervertebral disc height, associated with disc degeneration<sup>7</sup>, has been shown to lead to an increased load on the posterior bony elements of the lumbar spine and this may predispose the posterior bony elements to stress injuries<sup>8,9</sup>.

The prevalence of lumbar spondylolysis in the general population is thought to be between 3% and 6%<sup>10</sup>. Athletes have a higher prevalence of these injuries; Soler and Calderon<sup>11</sup> reported an overall prevalence of lumbar spondylolysis of 8% amongst elite Spanish athletes<sup>10,11</sup>. Sports other than cricket with a particularly high prevalence of lumbar stress injury include American Football, gymnastics, swimming, weightlifting and throwing sports<sup>12-18</sup>. It appears that fast bowlers in cricket suffer a specific pattern of stress injury of the lumbar partes interarticulares with the 4th and 5th lumbar vertebrae on the non-dominant side to the bowling arm being the most common site of injury<sup>19-21</sup>.

There is evidence of an association between a certain bowling action type, the mixed action, and radiological abnormalities of the lumbar spine in fast bowlers <sup>4-6, 22-25</sup>. The mixed fast bowling action is characterised by misalignment of the shoulders relative to the pelvis, and counter-rotation of the shoulders from a relatively front-on to a side-on alignment during the delivery stride of fast bowling <sup>22, 23</sup>. This technique is thought to place greater torsional stresses on the lumbar spine than a pure side-on or front-on type action. Mixed action bowlers have also been shown to have greater amounts of extension and side flexion of the spine during delivery of the ball <sup>26</sup>. However, the precise mechanism linking the kinematics of the trunk during fast bowling and the pathomechanics of low back injury is yet to be established.

Radiological investigation of lumbar posterior element stress injuries has, in the past, relied on a combination of radiography, bone scintigraphy (including single photon emission computed tomography (SPECT) and reverse gantry computed tomography (rg-CT) <sup>20, 27, 28</sup>. However, these modalities all involve exposure to significant doses of ionising radiation. MRI has increasingly been utilised in the investigation of a wide variety of spine pathologies including marrow oedema of the lumbar posterior elements (pedicles and partes interarticulares), lumbar spondylolysis, spondylolysthesis, disc degeneration and foraminal narrowing <sup>29-31</sup>, and has the advantage of not utilising or producing ionising radiation <sup>32</sup>.

Investigators have demonstrated that normal anatomy of the can be identified confidently using MRI <sup>33, 34</sup>. Recent studies comparing lumbar posterior element MRI, CT and SPECT findings and have concluded that MRI is a valid tool for identifying partes interarticulares pathology <sup>29, 35-37</sup>. MRI classification systems for lumbar posterior element stress injuries in young athletes <sup>38</sup> (see Table 2.1) and for assessing lumbar disc degeneration <sup>31</sup> have been evaluated and found to be both reproducible and reliable. The disc grading system shown in Table 2.2 is a 5-point scale based on MRI signal intensity, disc structure, the distinction between



nucleus and annulus, and disc height. Good intra- and inter-examiner agreement was found with this classification system based on an assessment of over 300 lumbar intervertebral discs<sup>31</sup>.

Most studies that have investigated radiological abnormalities of the lumbar spine in fast bowlers in cricket have examined groups of junior elite cricketers. The aim of this study was to compare MRI findings (of the lumbar discs and posterior elements) in a group of asymptomatic professional fast bowlers and in age-matched healthy, active controls. The intra-observer and inter-observer reliability of the MRI grading systems for the lumbar posterior elements and intervertebral discs were also assessed.

### **2.3 Materials and Methods**

Thirty six male professional fast bowlers, who were free of low back pain in the previous three months or at the time of testing formed the study group. The control group comprised 17 male athletic controls (none of the control group was involved in playing cricket regularly). The mean ( $\pm$ SD) age, height and mass of the fast bowlers were 26 ( $\pm$ 4) years, 186 ( $\pm$ 6)cm and 84( $\pm$ 7)kgs respectively. The mean age, height and mass of the control participants were 25( $\pm$ 5)years, 182 ( $\pm$ 5)cm and 79( $\pm$ 11) kgs respectively. Testing of participants took place at the end of the cricketer's professional season during which all participants in the fast bowling group bowled during matches or training sessions on an average of at least three days per week. Ethical approval for the study was provide by the Local Region Ethics Committee of the University of Nottingham, UK, Curtin University and Edith Cowan University, Western Australia.

The study and control groups both underwent MRI on a GE Medical Systems 1.5 Tesla MRI scanner using a standard protocol. This comprised sagittal and axial T1-weighted and sagittal STIR sequences; the sagittal sections covered out to the lateral border of the lower

lumbar posterior elements and were of 3 mm thickness. Sequence parameters were TR 500, TE 13 ms for the T1 weighted images; TR 8000, TE 50, TI 130 ms for the STIR images. The axial T1 weighted sections were obtained in a block covering from the superior vertebral endplate of L4 down to the inferior vertebral endplate of S1.

The MRI scans were assessed independently by two experienced musculoskeletal radiologists using classification systems adapted from Hollenburg *et al.*<sup>30</sup> (Table 2.1) and Pfirrmann *et al.*<sup>31</sup> (Table 2.2) for the lumbar posterior elements and discs respectively. Each radiologist, blinded to the results of the other examiner, performed the classifications twice within a three week period. Following assessment of the inter- and intra-examiner reliability, any discrepancies in the classifications were resolved by mutual agreement.

Table 2.1 MRI classification of the lumbar posterior elements. Adapted from Hollenburg *et al.*<sup>38</sup>

	Grade	MRI Appearance of the Lumbar Posterior Elements
Normal	0	No signal abnormality, intact
Chronic Stress Reaction	Oa	Cortical thickening, fibrotic/sclerotic marrow signal, intact
Sub-total acute stress fracture	I	Marrow oedema +/- signal changes in adjacent intact pedicle or articular process
	II	Marrow oedema + pars thinning, fragmentation or irregularity on T1 or STIR
Acute Stress Fracture	III	Marrow oedema + complete unilateral or bilateral spondylolysis
Chronic Stress Fracture	IV	Complete spondylolysis without marrow oedema (chronic united pars fractures)

Table 2.2 MRI Classification of lumbar intervertebral disc degeneration. Adapted from Pfirrmann *et al.* <sup>31</sup>

Degree of Degeneration	Grade	Structure	Distinction of Nucleus and Annulus	Signal Intensity (STIR)	Height of Intervertebral Disc
Normal	I	Homogenous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
	Ia	Homogenous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Reduced (normal transitional disc)
Mild	II	Inhomogeneous, with or without horizontal bands	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
Moderate	III	Inhomogeneous, grey	Unclear	Intermediate	Normal to slightly decreased
Severe	IV	Inhomogeneous, grey to black	Lost	Intermediate to hypointense	Normal to moderately decreased
	V	Inhomogeneous, black	Lost	Hypointense	Collapsed disc space

### 2.3.1 Statistics

Descriptive statistics were used to describe the prevalence of abnormal radiological features. Kappa co-efficient and percentage of agreement statistics were used to quantify the reliability of the intervertebral disc and partes interarticulares classification systems.

## **2.4 Results**

### *2.4.1 Lumbar spine MRI*

#### 2.4.1.1 Lumbar partes interarticulares findings

The results of the grading of the dominant and non-dominant side lumbar posterior elements for both the fast bowlers and control participants are displayed in Figure 2.1. The fast bowlers had a much higher prevalence of non-dominant side MRI abnormalities compared with the controls (81% v 36% of participants), whilst 81% of the dominant side partes appeared normal at all levels in the fast bowlers. The most common abnormality seen in the fast bowlers was multiple level non-dominant side partes interarticulares chronic stress reaction (Grade Oa - 53% of bowlers), followed by chronic stress fractures (Grade IV - 14%) and sub-total acute stress fracture (Grades I & II - 14%). In the fast bowlers, six of the seven chronic stress fractures were at L5 (two bilateral and two unilateral on the non-dominant side) and one was at the L4 spinal level. In comparison, chronic stress reactions were more common on the dominant side (24%, versus 12% on the non-dominant side), in the controls. None of the controls had sub-total stress fractures (Grades I & II) on either side. 12% of controls had bilateral chronic stress fractures (Grade IV), all at L5. None of the fast bowlers or controls had the MRI appearance of acute stress fracture of any of their partes interarticulares (Grade III).

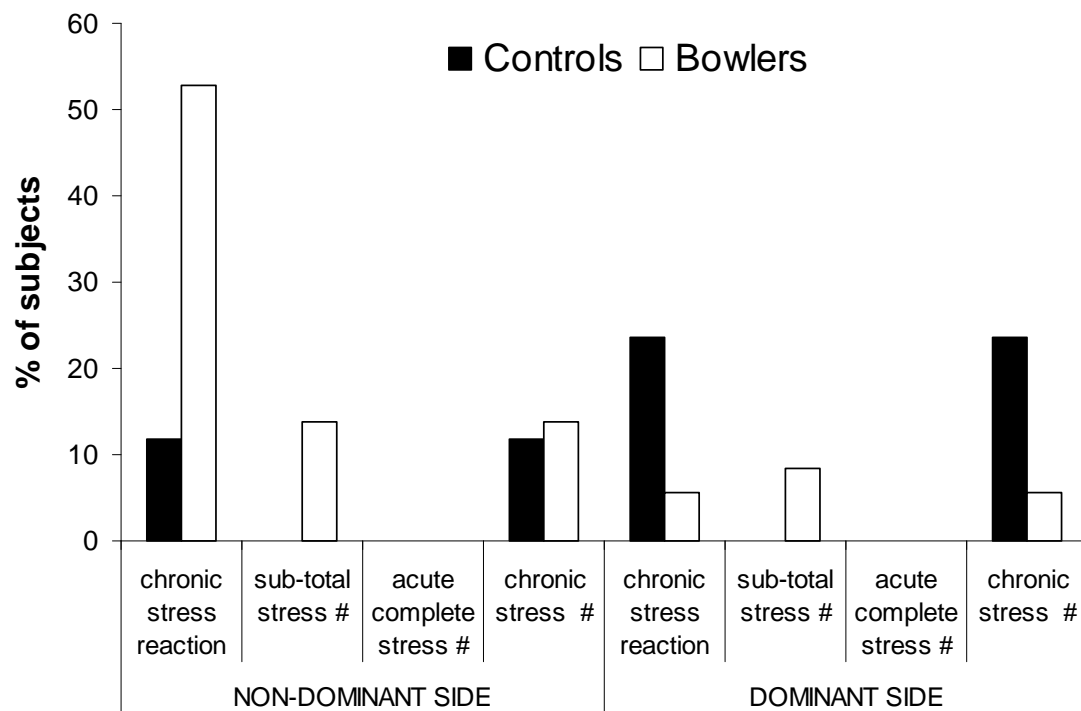


Figure 2.1 Dominant and non-dominant side partes interarticulares MRI appearance in control participants and professional fast bowlers.

Figure 2.1 shows the distribution by lumbar level of partes interarticulares MRI findings in the fast bowlers. In this group the majority of abnormalities were seen at the lower lumbar levels on the non-dominant side.

One of the fast bowlers had MRI abnormalities of the posterior bony elements that were deemed to require further investigation. The MRI appearance was of a cystic lesion at the non-dominant side L2/3 zygapophyseal joint along with the presence of a localised lesion at the tip of the non-dominant L3 inferior articular process. Subsequent CT scanning revealed an un-united fracture of the non-dominant L3 inferior articular process. Chronic stress changes were evident

in the posterior bony elements (partes interarticulares and pedicles) from L2 to L4 bilaterally and the zygapophyseal joints from L2 to L5 were moderately arthritic.

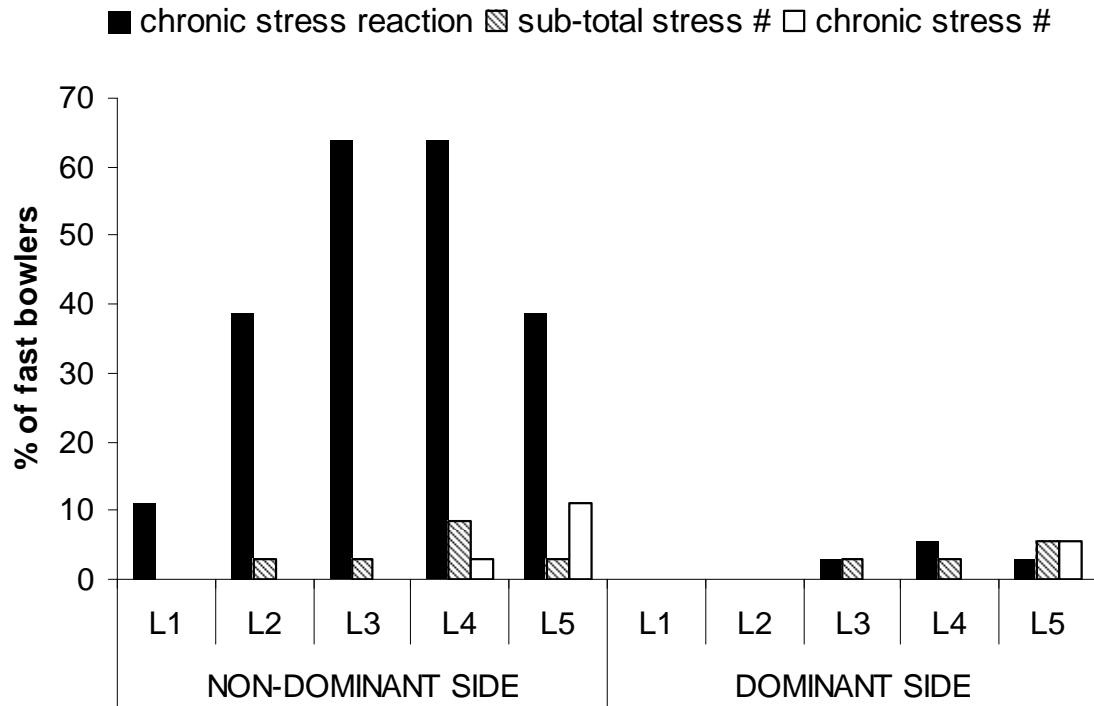


Figure 2.2 Percentage of partes interarticulares magnetic resonance abnormalities in fast bowlers: non-dominant and dominant side, at each lumbar level (L1 – L5).

#### 2.4.1.2 Lumbar intervertebral disc MRI findings

The results of the grading of the lumbar intervertebral discs from the MRI images of the lumbar spines of the cohort of active control participants and fast bowlers are displayed in Figure 2.3. Sixty-one percent of fast bowlers, compared with 53% of controls, had MRI abnormalities of the intervertebral disc at a least one lumbar level. However, 33% of fast bowlers as opposed to 12% of controls had severe lumbar disc degeneration (Grade IV-V), with 17% of fast bowlers having severe multiple level disc degeneration. A further 17% of fast

bowlers and 36% of controls were graded as having moderate disc degeneration (Grade III) at one or more lumbar levels. None of the controls and 11% of fast bowlers had mild disc degeneration (Grade II). The majority of degenerative discs were found at the lower lumbar levels i.e. L4/5 & L5/S1, in both the fast bowlers (62%) and the control group (90%).

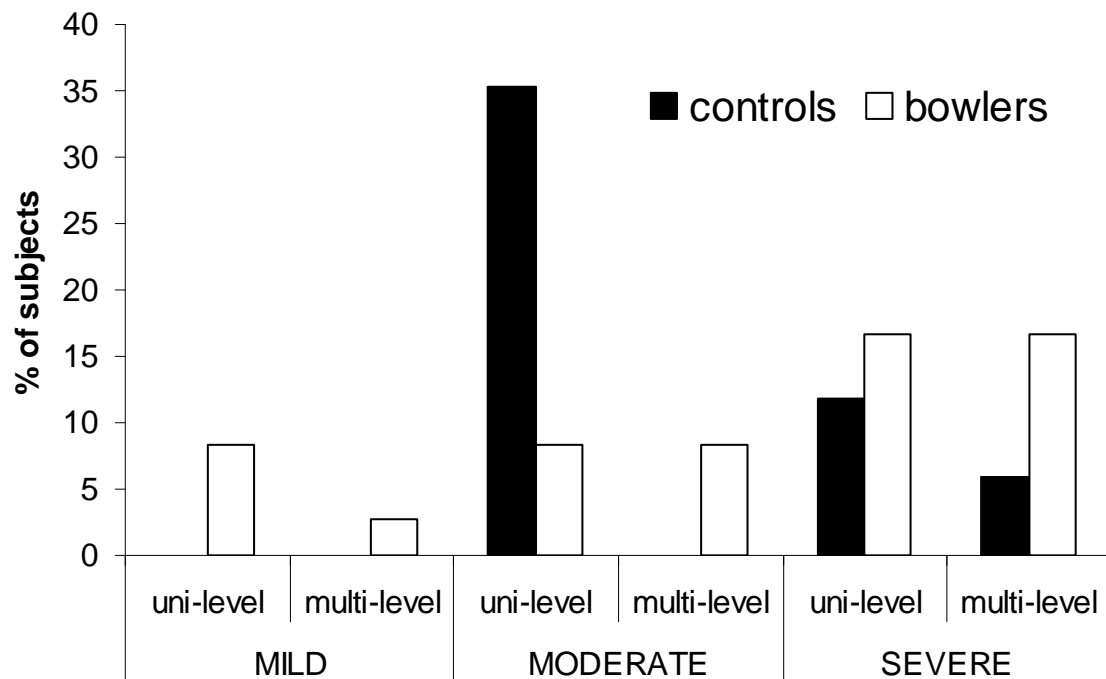


Figure 2.3 Percentages of controls and fast bowlers with lumbar intervertebral disc degeneration.

#### 2.4.1.3 Relationships between lumbar intervertebral disc and partes interarticulares MRI appearance.

Only 8% of fast bowlers, compared with 24% of controls, had a normal MRI appearance of both the lumbar intervertebral discs and posterior elements at all lumbar levels. Half of the fast bowlers who had multiple level partes interarticulares stress injuries did not have any

evidence of disc degeneration. All of the fast bowlers, versus only 50% of the controls, who had chronic stress fractures had concurrent severe disc degeneration.

#### *2.4.2 Reliability of the MRI Disc and partes interarticulares classification systems*

The Cohen Kappa co-efficient and percentage agreement statistics for the lumbar intervertebral disc grading indicated that there was substantial reliability<sup>39</sup> of the intra-examiner classification (0.6, 90%) and moderate reliability of inter-examiner disc classification (0.5, 87%). There was substantial reliability of both the intra- (0.7, 96%) and inter-examiner (0.6, 95%) partes interarticulares classification.

## **2.5 Discussion**

### *2.5.1 Lumbar Partes Interarticulares MRI Findings*

Several authors have proposed that posterior element stress injuries develop in stages with the initial insults from repetitive trauma to these structures being radiographically occult on X-Ray or CT images<sup>29, 40-42</sup>. Early stage lumbar posterior element lesions, sometimes referred to as acute stress reactions, such as bone marrow oedema (Grade I) and oedema with thinning and fragmentation of the pars or adjacent pedicle (Grade II), had a prevalence of 22% in the group of fast bowlers. What was particularly striking was the very high prevalence of multi-level cortical thickening along with sclerosis and marrow fibrosis of the partes interarticulares on the non-bowling arm side in the fast bowlers. Identification of such changes has not been reported in previous MRI studies of partes interarticulares pathology; their observation in this study was probably aided by the marked asymmetry in individual participants, enabling ready comparison to be made with the contralateral side. Elliott *et al.*<sup>6</sup> performed CT scans on a group of 20 fast bowlers (mean age 17.9 years) and reported a 30% prevalence of L4 or L5 pedicle sclerosis, suggested to indicate an evolving or resolving stress fracture. However, it is not known whether



this type of lesion, termed ‘chronic stress reaction’ in this paper, is a precursor to acute stress fracture or simply a normal bony adaptation to the repeated asymmetrical stresses placed on the posterior elements of the lumbar spine by fast bowling in cricket<sup>26</sup>.

It appears that acute bone stress reactions, traditionally identified with SPECT<sup>43</sup> can also be identified with MRI. This supports the assertion of Campbell *et al.*<sup>37</sup> that there does not seem to be a role for SPECT scanning in the investigation of these types of injuries. Chronic stress fractures can also be identified on MRI. However, as demonstrated in the case cited in this study, subsequent CT scanning may be indicated to provide more precise imaging of the bony architecture.

Gregory *et al.*<sup>43</sup> stated that un-united stress fractures may require operative stabilisation in the presence of ongoing back pain in fast bowlers. The results of this study support the findings of a CT study by Millson *et al.*<sup>44</sup> which revealed that fast bowlers can be asymptomatic despite having un-united chronic lumbar stress fractures. Five asymptomatic fast bowlers in this study had chronic stress fractures. Therefore, other possible sources of low back pain should be excluded before progressing to operative stabilisation of chronic stress fractures. That none of the fast bowlers, or asymptomatic controls, in this study had evidence of acute complete lumbar stress fracture, may indicate that it is these acute stress injuries that cause pain and limit sporting activity.

Both the fast bowling and control groups had a similar prevalence of chronic stress fracture to that previously reported for similar aged athletic participants<sup>11</sup>. Interestingly, in the control participants all those who had chronic stress fractures had them bilaterally at L5 whilst two of the fast bowlers (6%) had bilateral chronic stress fractures at L5 and three others had unilateral, non-dominant side fractures. Although it is not possible to identify which of the bilateral stress fractures were developmental from those which may have arisen as a result of the

participants' sporting or occupational activities, it is highly likely that the unilateral fractures in the fast bowlers were caused by that activity.

### 2.5.2 *Lumbar Intervertebral Disc MRI Findings*

Elliott *et al.*<sup>6</sup> reported a 65% prevalence of intervertebral disc abnormality, at one or more lumbar level, in a group of young fast bowlers (mean age 17.9 years) and Annear *et al.*<sup>45</sup> reported that 70% of retired elite fast bowlers (mean age 48.3 years) had X-ray evidence of disc degeneration. Other MRI studies of the lumbar intervertebral discs have reported abnormality prevalence rates of between 35%<sup>46</sup> and 62%<sup>47</sup> in similar aged participants to those in this study. Although the fast bowlers and control participants in this study had similar overall prevalence of lumbar disc abnormalities, the fast bowlers had more severe disc degeneration and a much higher rate of multi-level disc abnormalities. It would appear that fast bowling is a cause of premature lumbar disc degeneration. However, as the fast bowlers in this study were all able to continue to bowl despite severe disc degeneration, the relationship between symptoms and disc pathology remains unclear; other modern imaging techniques (such as dynamic MRI, functional MRI, diffusion imaging, and magnetic resonance spectroscopy) may, in time, help to elucidate the relationship between disc imaging findings and symptoms<sup>48</sup>.

### 2.5.3 *Relationships between Lumbar Intervertebral Disc and Partes Interarticulares MRI appearance.*

It has previously been suggested that a loss of disc height associated with intervertebral disc degeneration leads to increased stress being placed on the posterior bony elements of the lumbar spine<sup>8,9</sup>. However, a high proportion (50%) of the fast bowlers in this study who had lumbar chronic stress reaction and sub-total stress fracture had normal disc appearance and height. In addition, half of the 24% of control participants who had chronic lumbar stress fractures did not have evidence of disc degeneration. The fact that all chronic bilateral stress fractures in fast bowlers were associated with severe disc degeneration at that spinal level, could

indicate that an excess of segmental motion caused by un-united fracture precipitates disc degeneration.

#### *2.5.4 Reliability of the MRI Disc and Partes Interarticulares Classification Systems*

Although not achieving Kappa co-efficient scores as high as the original authors<sup>31, 38</sup>, both the adapted partes interarticulares and intervertebral disc classification systems used in this study had acceptable reliability and could be useful tools for the staging and re-assessment of lumbar disc and posterior element pathology in athletes.

## **2.6 Conclusions**

Fast bowlers in cricket have a high prevalence of multi-level, non-dominant side chronic stress reactions and stress injuries in the lumbar posterior elements. Disc degeneration is also present in higher proportions than in non fast bowlers. However, disc degeneration is not a necessary precursor to lumbar stress injury. Fast bowlers can continue to bowl with chronic lumbar stress fractures, however, fast bowling with bilateral stress fractures may precipitate severe disc degeneration. The clinical relevance of MRI abnormalities is not clear and further prospective studies, possibly utilising dynamic imaging modalities, are required to establish the relationship between pain, function and partes interarticulares and disc findings.

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## **CHAPTER 3 - Study II**

The measurement of the morphology of the lumbar paraspinal muscles has become the focus of several recent investigations into the aetiology of low back pain. Imaging modalities such as CT, US and MRI have been used to quantify paraspinal muscle CSA however few investigators have sought to measure the functional CSA (FCSA, the area of muscle isolated from fat). MRI has advantages over CT in that it does not involve exposure to ionising radiation and allows better tissue type discrimination and localisation than US. However, the reliability and validity of determining the FCSA of the lumbar paraspinal muscles using MR imaging has yet to be reported. Therefore, the aim of this study was to investigate the use of MRI and image processing software to determine the functional FCSA of the lumbar paraspinal muscles.

**An investigation into the use of MR imaging to determine the functional cross sectional area of lumbar paraspinal muscles.**

Adapted from: Ranson CA, Burnett AF, Kerslake RW, Batt ME and O'Sullivan PB.: \*An investigation into the use of MR imaging to determine the functional cross sectional area of lumbar paraspinal muscles. *European Spine Journal*. 15:764-773, 2006.

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The original publication is available at [www.springerlink.com](http://www.springerlink.com).

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### 3.1 Abstract

The purpose of this study was to investigate the use of magnetic resonance (MR) imaging and image processing software to determine the functional cross-sectional area (FCSA) (the area of muscle isolated from fat) of the lumbar paraspinal muscles. The measurement of the morphology of the lumbar paraspinal muscles has become the focus of several recent investigations into the aetiology of low back pain. However, the reliability and validity of determining the FCSA of the lumbar paraspinal muscles using MR imaging has yet to be reported. T2 axial MR scans at the L1-S1 spinal levels of six participants were obtained using identical MR systems and scanning parameters. Lean paraspinal muscle, vertebral body bone and intermuscular fat was manually segmented using image analysis software to assign a grey scale range to the MR signal intensity emitted by each tissue type. The resultant grey scale range for muscle was used to determine FCSA measurements for each of the paraspinal muscles, psoas, quadratus lumborum, erector spinae and lumbar multifidus on each scan slice. As various biological, instrument and measurement factors can affect MR signal intensity, a sensitivity analysis was conducted to determine the error associated in calculating FCSA for paraspinal muscle using a discrete grey scale range. CSA and FCSA measurements were repeated three times and reliability indices for the FCSA measurements were obtained, showing excellent reliability ICC (mean = 0.97, range 0.90–0.99) and %SEM (mean = 2.6%, range 0.7–4.8%). In addition, the error associated with miscalculation of the grey scale range for the MR signal intensity of muscle was calculated and found to be low with an error of 20 grey scale units at the upper end of the muscle's grey scale range resulting in a very small error in the measured muscle FCSA. The method presented in this paper has a variety of practical applications in areas such as evidence-based rehabilitation, biomechanical modelling and the determination of segmental inertial parameters.

### 3.2 Introduction

The measurement of the morphology of the lumbar paraspinal muscles has become the focus of several recent investigations into the aetiology of low back pain (LBP) <sup>1-7</sup>. Muscles in this group, consisting of the psoas, quadratus lumborum, iliocostalis lumborum, longissimus lumborum and the lumbar multifidus, can have a direct influence on segmental stability and control of the lumbar spine due to their attachments to the spinal column. Coordinated, co-contraction of the lumbar paraspinal muscles with the abdominal wall muscles is thought to have a stabilising effect on the lumbar spinal segments therefore, providing a safe platform for trunk movement <sup>8,9</sup>. It has been suggested that dysfunction of these muscles is a significant factor in the aetiology and chronicity of LBP <sup>2, 4, 10, 11</sup>.

Cross-sectional area (CSA) asymmetries of certain lumbar paraspinal muscles have previously been associated with the presence of LBP <sup>4, 5, 12-15</sup>. These asymmetries are thought to be a quantitative manifestation of lumbar paraspinal muscle dysfunction. Hides *et al.* <sup>12</sup> used real time ultrasound to measure the CSA of the lumbar multifidus from L2 to S1 in participants with acute, first episode, LBP. The authors reported uni-segmental atrophy, represented by a reduced lumbar multifidus CSA, which correlated with the symptomatic side of the body and spinal level. In a subsequent study <sup>4</sup>, localised atrophy of the lumbar multifidus was shown not to spontaneously recover following the resolution of LBP. This phenomenon was thought to be sequelae to pain-induced inhibition of this muscle <sup>4</sup>. A deficit in the capacity of the segmental stabilising muscles of the lumbar spine has been proposed as a mechanism for recurrent low back injury <sup>4, 13</sup>.

Investigations into the aetiology of LBP have also revealed that significant atrophy of specific lumbar paraspinal muscles can occur without a reduction in the total CSA within the muscles' fascial boundaries <sup>5, 15</sup>. These authors described paraspinal muscle atrophy in terms of replacement of muscle with fat and fibrous tissue, which would result in reduced functional contractility of muscle. Therefore, a measure of the functional cross-sectional area

(FCSA) i.e. the area of lean muscle tissue within a muscle's fascial boundaries would be a better indicator of the muscle's contractile ability.

Imaging techniques such as ultrasound, computed tomography (CT) and magnetic resonance (MR) allow *in-vivo* calculation of low back muscle CSAs. The use of ultrasound is limited to the examination of superficial muscles and the resolution of the resulting images is generally low which can make tissue type discrimination difficult<sup>16</sup>. CT allows high-resolution tissue type discrimination within trunk muscle fascial boundaries<sup>13</sup>. However, CT involves exposure to significant doses of ionising radiation and is therefore a less than ideal technique for assessing the morphology of spinal muscles in asymptomatic participants. Previous MR studies have reported atrophy of selected lumbar paraspinal muscles, in terms of replacement of muscle bulk with fat and fibrous tissue, and have relied upon radiologist assessment and grading of the muscles' appearance i.e. degree of muscle atrophy and fat infiltration, without quantitative assessment of the intramuscular morphology<sup>5, 15</sup>.

Segmentation (or tissue classification) is the process whereby various tissues visible on either a CT or MR image are distinguishable by the signal intensity they emit<sup>17-22</sup>. Danneels *et al.*<sup>13</sup> conducted a study that used CT in conjunction with image processing software to produce quantitative measurement of "low-fat" CSA's of low back muscles. Their approach involved eliminating pixels within the fascial boundary with grey scale values that were thought to represent fat. In the Daneels' study however, the method of determining grey scale values for the different tissue types was not described in detail.

The signal intensity of each pixel from an MR image can be assigned a grey scale value using image analysis software<sup>17, 18, 20, 22</sup>. Segmentation is a complex area in automated MR image analysis due to potential problems such as heterogeneous signal intensities in tissues and the fact that individual pixels of an MR image may contain two or more anatomical structures (the partial volume effect)<sup>17, 18, 22-24</sup>. Regardless of these concerns, recent investigations using MR to determine inertial properties of body segments have identified tissue types using discrete grey scale ranges for signal intensity emitted by various

tissues including fat, bone and muscle<sup>25,26</sup>. More sophisticated methods of MR image tissue segmentation have been successfully utilised in the area of brain research. Harris *et al.*<sup>17</sup> and Meier and Guttman<sup>23</sup> developed methods to automatically segment MR images of the brain according to the signal intensity of manually identified areas of homogenous white matter, grey matter and cerebrospinal fluid.

Despite the use of identical MR systems and scanning parameters, homogeneous tissue may have varying signal intensity between participants and from one scan slice within participants. Further, the MR signal intensity for muscle may vary depending on a variety of factors such as where the tissue lies within the scan area and the intensity of metabolic activity of the muscle during scanning<sup>17,18,27</sup>. The abovementioned biological and measurement effects on MR signal intensity pose a significant problem for researchers wishing to measure the FCSA of the paraspinal muscles, as isolating the area of only one tissue type requires a grey scale range for that tissue type to be identified.

Therefore, the purpose of this investigation was to determine a viable method to analyse the intramuscular morphology of the lumbar paraspinal muscles using MR imaging. In the attempt to determine the preferred method of ensuring that non-contractile tissue was largely eliminated from CSA measurements, two methods of obtaining a grey scale range for MR the signal intensity of lean paraspinal muscle were investigated. Furthermore, the reliability of what was determined to be the preferred method was examined.

### **3.3 Materials and Methods**

#### **3.3.1 Participants**

The MR scans used in this study were collected as part of a larger study investigating the relationship between paraspinal muscle morphology and low back injury in professional fast bowlers in the game of cricket. The participants were six, male, professional fast bowlers, aged between 20 and 28 years of age, who were fit to bowl at the

time of data collection. Ethical approval had been provided for the larger study by the Local Region Ethics Committee of the University of Nottingham, UK, Curtin University and Edith Cowan University, Western Australia.

### *3.3.2 Scanning protocol and image analysis*

Axial T2 weighted MR scans of the six participants were taken at seven spinal levels; they being the lower vertebral end plate of L1 to L5 and the upper vertebral endplate of L5 and S1 (Figure 3.1). Following 30 minutes of quiet sitting, the participants were positioned supine in the MR scanner with their hips and knees flexed to allow their normal lumbar lordosis to be comfortably maintained. A spirit level was used to ensure a level trunk and pelvis position. These scans were all obtained during one data collection session using a General Electric 1.5 tesla MR scanner employing a fast spin echo sequence of TR 4000 ms, Teef 120 ms, 5mm slice thickness, 512 x 512 matrix. The field of view for the scans (33cm x 33cm) was set so that all paraspinal muscles of interest were visible. These muscles were the left and right psoas major, quadratus lumborum, multifidus and the combined bulk of the erector spinae muscles iliocostalis and longissimus. The iliocostalis and longissimus were grouped as their separate fascial boundaries were difficult to determine on some scans. Images were saved as 16 Bit DICOM files for later analysis.



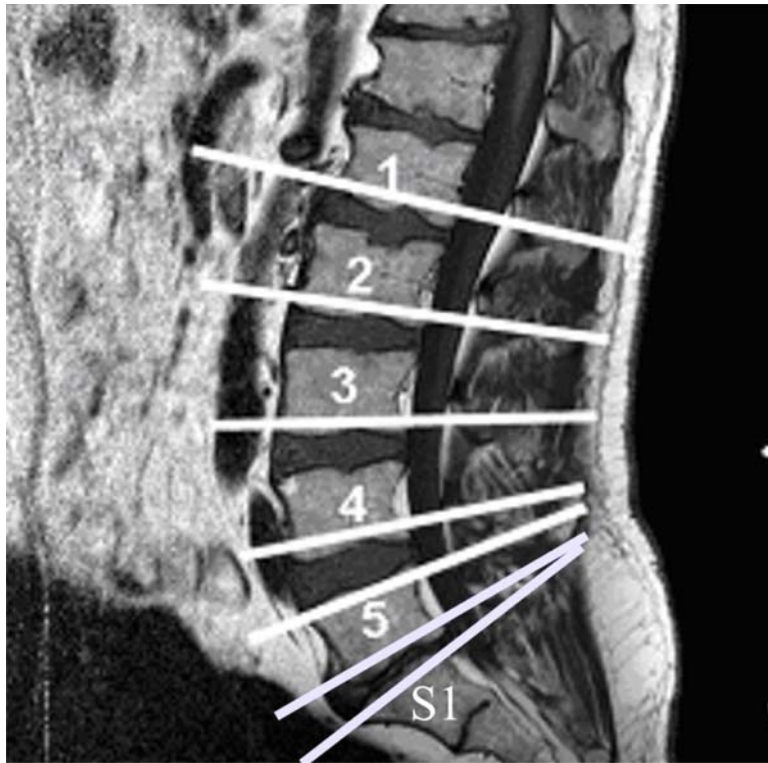


Figure 3.1 Scout view of the axial T2 MR scans. Scans were taken at the inferior vertebral endplate of L1 to L5 and the superior vertebral endplate of L5 and S1.

Image J V1.3 (National Institutes of Health, USA) software installed on a notebook computer, running a 2.4GHz Intel Pentium IV processor, was used to analyse the scans. The scans were imported into the software program and enlarged using a 2:1 zoom ratio. The scale of the image processing software's measurement function was calibrated by dividing the number of pixels contained along the vertical and horizontal lengths of the images (512), by the scans' known height and width (33cm x 33cm) to give a scale of 15.52 pixels/cm.

Muscle CSA measurements at each spinal level were determined by outlining the fascial boundary of the abovementioned muscles (Figure 3.2) and using the measurement function of the image processing software. The quadratus lumborum and psoas muscles were only measured at the L1 to L4 and L1 to L5 spinal levels respectively, as these muscles were not clearly discernible below these levels.



Figure 3.2 Example regions of interest used for calculating the cross-sectional area of the psoas, quadratus lumborum (QL), erector spinae (ES - combined iliocostalis and longissimus) and lumbar multifidus (Mtx) muscles on an L3 axial MR image.

### 3.3.3 *Determination of the grey scale range for the MR signal intensity of lean paraspinal muscle*

In this part of the investigation two methods of determining the grey scale range for the MR signal intensity of lean paraspinal muscle were compared. The aim was to determine the preferred method of identifying the grey scale range for the MR signal intensity of lean muscle in order to calculate the FCSA of the paraspinal muscles. This method should be reliable, accurate and relatively time efficient.

The first method (Method 1) involved determining the grey scale range for the MR signal intensity of lean paraspinal muscle across the entire set of MR scans used in this study. This was based on manual segmentation of the three most prevalent homogenous tissue types within the field of view of the scan. They being vertebral body bone, paraspinal

muscle and intermuscular fat. In order to differentiate lean paraspinal muscle from other tissue likely to be contained within the field of view of the scans, the largest possible region of interest (ROI) of homogenous bone within the vertebral body, lean paraspinal muscle and intermuscular fat, on each scan slice was manually identified in six participants i.e. a total of 42 samples per tissue type were analysed (Figure 3.3). The resulting grey scale values for the three tissue types were then normalised to the total number of pixels analysed to allow direct comparison of tissue type. From this data, grey scale ranges for the MR signal intensity of three tissue types, across the entire set of scan, were determined.

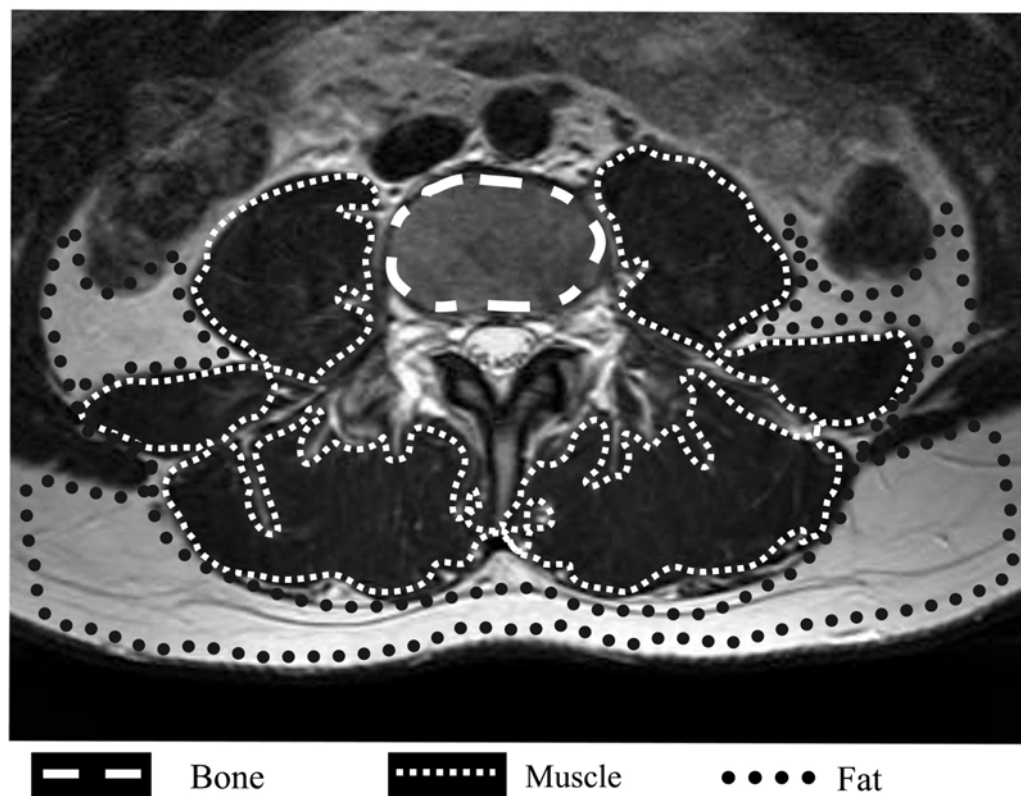


Figure 3.3 Example regions of interest (ROI) used for the calculation of discrete and slice-specific grey scale ranges for bone, muscle and fat from an L3 axial T2 MR scan.

Due to the nature of MR it is possible that the signal intensity, and hence grey scale range, for the same tissue type can vary from participant to participant, from scan level to

level and even within the same scan slice. Therefore, in the second part of this section of the study, a second sampling method for determining a grey scale range for the MR signal intensity of lean paraspinal muscle was investigated.

The second method (Method 2) involved determining a grey scale range for the MR signal intensity of lean muscle that was specific to each scan slice. These slice-specific grey scale ranges were determined from the ROI that were considered to be the largest area of homogenous muscle within the combined bulk of all the paraspinal muscles visible on each scan slice (Figure 3.3).

#### *3.3.4 Method reliability*

The same observer measured CSA and FCSA three times for each muscle, on each scan slice, for each participant, in random order. FCSA measurements were calculated by thresholding the CSA to include only pixels that were within the grey scale range for lean muscle tissue previously determined using Method 1 above. A mean of the three CSA and FCSA measurements for each paraspinal muscle examined was taken for further analysis.

#### *3.3.5 Sensitivity analysis*

To determine the error in obtaining FCSA measurements using a discrete grey scale range which was generated from the analysis of MR signal intensity found from Method 1, a sensitivity analysis was undertaken. As described later in the results section, the resulting discrete grey scale range for the MR signal intensity of lean paraspinal muscle was found to be 0-120 for this set of scans. Therefore, FCSA measurements obtained using this discrete grey scale range were termed FCSA120.

Following evaluation of the methods in the first part of the study, it was deemed that the slice-specific grey scale ranges for muscle (Method 2) were likely to produce the most accurate FCSA measurements. Therefore, further FCSA measurements were obtained using these slice-specific grey scale ranges. To enable an analysis of the degree of error in the FCSA120 measurements caused by using a discrete grey scale range rather than a slice-

specific grey scale range for muscle, further FCSA measurements were calculated using the grey scale ranges 0-60, 0-80, 0-100, 0-140 and 0-160. These measurements were then expressed as a percentage of the FCSA measurements obtained using the slice-specific grey scale range for lean muscle (Method 2).

### 3.3.6 Statistical analysis

Intra class correlation coefficient (ICC) values for the three trials for CSA and FCSA120 for each muscle of interest were calculated using SPSS V10.0. The absolute Standard Error of Measurement (SEM) and the relative SEM (%SEM)<sup>28</sup>, for the three trials of CSA and FCSA120 measurements, were calculated from the ICC as follows: -

$$SEM = S_x \sqrt{1 - ICC}$$

Where,  $S_x$  was the pooled standard deviation. The %SEM was then calculated by the following:-

$$\%SEM = SEM / (X_{mean}) * 100$$

Where,  $X_{mean}$  was the pooled mean of the three measurements.

## 3.4 Results

### 3.4.1 Determination of the grey scale range for the MR signal intensity of lean paraspinal muscle

The grey scale ranges for the combined samples of bone, lean paraspinal muscle, and inter-muscular fat from each of the 42 scan slices obtained using Method 1 are shown in Figure 3.4. The overlap of the upper portion of the grey scale range for muscle and the lower portion of the grey scale range for fat on this set of scans spanned from 53 to 160 on the grey scale. However, the amount of pixels representing fat in this overlapping area of the curves was relatively small up to 120 on the grey scale, at which point the number of pixels representing muscle became small as those representing fat began to rise. Therefore, the grey

scale range for lean paraspinal muscle for the entire set of scans, across the six participants, was determined to be 0-120. Similarly, the grey scale range for bone on this set of scans was determined to be 10 to 255 and the grey scale range for fat was determined to be 74 to 660.

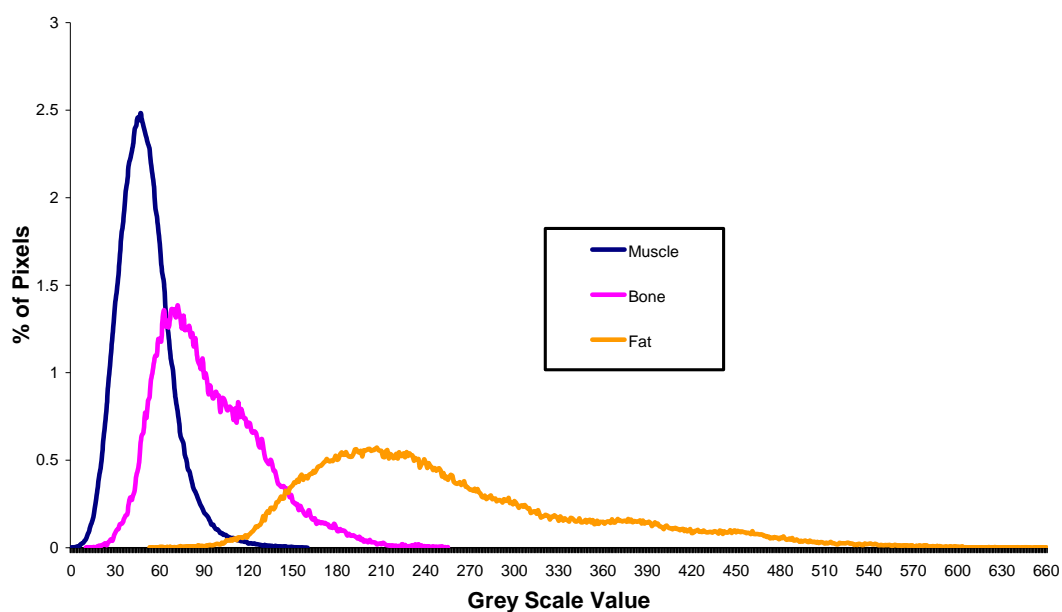


Figure 3.4 Grey scale values for the MR signal intensity of bone, lean paraspinal muscle and fat across the entire set of scans

Table 3.1 shows the slice-specific grey scale ranges for muscle for each participant determined using Method 2.

Table 3.1 Slice-specific grey scale ranges for lean paraspinal muscle.

Spinal Level	Participant					
	1	2	3	4	5	6
L1	1 - 103	1 - 128	2 - 104	5 - 130	1 - 123	3 - 132
L2	3 - 115	7 - 138	3 - 124	3 - 124	5 - 139	4 - 144
L3	5 - 151	2 - 154	5 - 142	6 - 138	5 - 134	5 - 159
L4	7 - 138	6 - 149	3 - 132	8 - 131	4 - 135	1 - 125
L5 Superior	9 - 112	5 - 137	5 - 135	4 - 126	6 - 134	6 - 124
L5 Inferior	8 - 116	6 - 140	6 - 108	12 - 121	5 - 151	6 - 116
S1	5 - 126	19 - 101	17 - 101	12 - 109	18 - 161	16 - 131

#### 3.4.2 Technique reliability

ICC and %SEM values for the mean CSA and FCSEA120 for each muscle of interest are summarised in Tables 3.2 and 3.3 respectively. Both CSA and FCSEA120 showed excellent reliability in both indices, CSA ICC (mean = 0.96, range 0.89-0.99), %SEM (mean = 3.1%, range 1.0-4.9%) and FCSEA120 ICC (mean = 0.97, range 0.90–0.99), %SEM (mean = 2.6%, range 0.7–4.8%). There was a significant correlation ( $r = -0.72$ ,  $p < 0.05$ ) between mean FCSEA120 and %SEM indicating that muscles with a lower FCSEA120 had a higher %SEM. The L4 multifidus was the most notable exception to this trend, as it showed a relatively large FCSEA120 and a relatively large %SEM.

Table 3.2 The intra-class correlation co-efficient (ICC) and percentage standard error of measurement (%SEM) for the cross sectional area (CSA) of the lumbar paraspinal muscles.

Spinal Level	Psoas					Quadratus Lumborum					Erector Spinae					Multifidus				
	L CSA	R CSA	Mean CSA	ICC	%SEM	L CSA	R CSA	Mean CSA	ICC	%SEM	L CSA	R CSA	Mean CSA	ICC	%SEM	L CSA	R CSA	Mean CSA	ICC	%SEM
L1	4.00	3.50	3.75	0.89	4.81	3.61	3.78	3.69	0.95	4.95	23.58	22.38	22.98	0.91	2.78	3.44	3.49	3.47	0.90	4.66
L2	9.75	9.17	9.46	0.96	2.00	5.43	5.90	5.68	0.93	4.73	23.35	24.19	23.77	0.98	1.73	4.97	5.21	5.09	0.95	4.37
L3	16.26	16.88	16.57	0.97	1.78	6.94	7.06	7.06	0.97	3.96	19.89	22.53	21.21	0.99	2.15	9.62	9.58	9.60	0.97	3.61
L4	24.11	24.08	24.10	0.98	1.55	8.25	9.22	8.63	0.95	3.41	17.53	18.07	17.80	0.97	3.45	13.74	14.17	13.95	0.90	4.83
L5 Sup	25.84	26.09	25.96	0.99	1.31	*	*	*	*	*	14.97	16.27	15.62	0.96	1.19	12.10	12.12	12.11	0.98	1.08
L5 Inf	24.79	24.02	24.41	0.99	1.10	*	*	*	*	*	11.27	14.13	12.70	0.99	2.97	14.24	13.63	13.94	0.97	3.34
S1	*	*	*	*	*	*	*	*	*	*	8.53	8.24	8.38	0.99	3.99	14.49	13.80	14.14	0.99	3.01
Mean	17.46	17.29	17.37	0.96	2.09	6.06	6.49	6.26	0.95	4.26	17.02	17.97	17.50	0.97	2.61	10.37	10.29	10.33	0.95	3.56

\* No measurement taken at these levels.



Table 3.3 The intra-class correlation co-efficient (ICC) and percentage standard error of measurement (%SEM) for the functional cross sectional area (FCSA) of the lumbar paraspinal muscles.

Spinal Level	Psoas					Quadratus Lumborum					Erector Spinae					Multifidus				
	L FCSA	R FCSA	Mean FCSA	ICC	%SEM	L FCSA	R FCSA	Mean FCSA	ICC	%SEM	L FCSA	R FCSA	Mean FCSA	ICC	%SEM	L FCSA	R FCSA	Mean FCSA	ICC	%SEM
L1	3.98	3.49	3.73	0.90	4.75	3.43	3.83	3.63	0.96	4.75	22.57	21.70	22.13	0.95	2.31	3.24	3.36	3.30	0.95	3.51
L2	9.57	9.01	9.29	0.98	1.45	5.42	5.58	5.50	0.96	3.70	21.60	22.87	22.23	0.99	1.38	4.55	4.77	4.66	0.97	3.55
L3	15.85	16.36	16.10	0.99	1.34	6.34	7.26	6.80	0.98	3.00	18.47	20.56	19.52	0.99	1.87	8.58	8.53	8.55	0.98	3.31
L4	23.64	23.49	23.56	0.99	1.26	8.02	8.85	8.43	0.97	2.78	15.99	16.85	16.42	0.99	2.21	12.61	12.87	12.74	0.94	4.80
L5 Sup	26.20	25.04	25.62	0.99	1.05	*	*	*	*	*	13.46	14.83	14.14	0.99	0.72	11.57	11.48	11.52	0.99	0.90
L5 Inf	25.74	25.01	25.38	0.99	1.23	*	*	*	*	*	9.40	12.17	10.79	0.99	2.33	13.42	12.35	12.88	0.99	2.84
S1	*	*	*	*	*	*	*	*	*	*	6.58	6.47	6.52	0.99	3.28	13.03	12.47	12.75	0.99	2.33
Mean	17.49	17.07	17.28	0.97	1.85	5.80	6.38	6.09	0.97	3.56	15.44	16.49	15.97	0.98	2.01	9.57	9.40	9.49	0.97	3.03

\* No measurement taken at these levels

### 3.4.3 Sensitivity analysis

The mean FCSA determined using the discrete grey scale ranges of, 0-60, 0-80, 0-100, 0-120, 0-140 and 0-160 as a percentage of the FCSA determined using the slice-specific grey scale range are presented in Figure 3.5. From this figure it can be seen that muscle FCSA determined using the 0–100, 0-120 and 0–140 discrete grey scale ranges were respectively, 95%, 99% and 101%, of the FCSA determined using the slice-specific grey scale range. This indicates that an error of 20 grey scale units at the upper end of the muscle’s grey scale range would result in a very small error in the measured muscle FCSA. Conversely, if the upper limit of the muscle grey scale range was set below the 100 value the potential for error in determining the muscle FCSA from this set of scans, would be far larger.

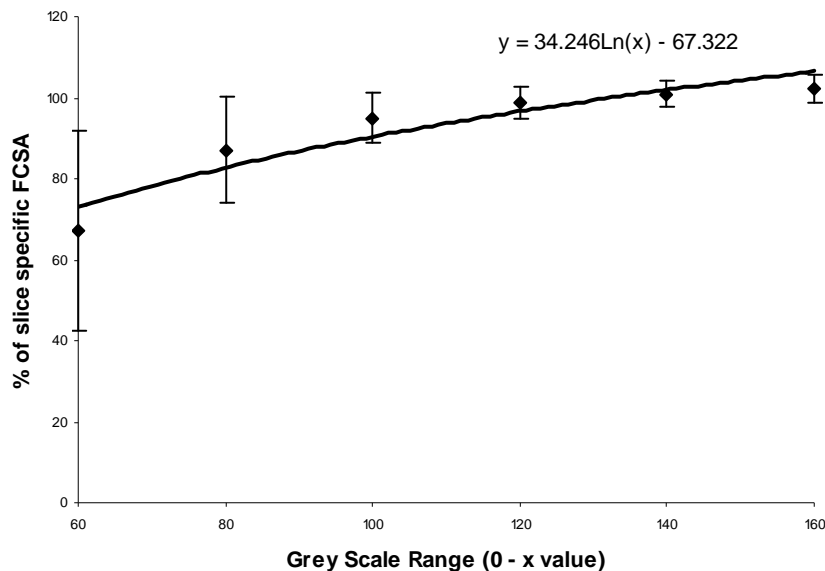


Figure 3.5 FCSA measurements determined using the discrete grey scale ranges of, 0-60, 0-80, 0-100, 0-120, 0-140 and 0-160 as a percentage of the FCSA measurements determined using the slice-specific grey scale range for muscle.

### 3.5 Discussion

#### 3.5.1 *Determination of the grey scale range for the MR signal intensity of lean paraspinal muscle*

Segmentation (or tissue classification) has been a complex area in automated quantitative MR imaging applications due to problems such as heterogeneous signal intensities in tissues and the partial volume effect<sup>17, 18, 22, 23</sup>. The overlap of the grey scale range for the MR signal intensity of the bone, muscle and fat samples, as shown in Figure 3.4, can be attributed to a variety of factors. Although care was taken to exclude large areas of tissue other than muscle and fat from the respective sample ROI (Figure 3.3) the muscle samples would almost certainly have contained areas of other tissue such as intramuscular fat, fibrous and nervous tissue, whilst fat samples would have also contained small areas of tissue such as blood vessels and nervous tissue. This, combined with the partial volume effect i.e. the presence of pixels containing more than one tissue type whose grey scale value is the average of the included tissues', may help to explain the small degree of overlap of the grey scale ranges for muscle and fat. The considerable overlap between the grey scale range for muscle and vertebral body bone should not influence the paraspinal muscle CSA and FCSA, as careful outlining of the fascial boundaries of the paraspinal muscles should ensure that no bony tissue is included in the ROI used to obtain these measurements.

In an attempt to find the preferred and most reliable method of obtaining FCSA measurements of the paraspinal muscles, two methods of determining a grey scale range for the signal intensity of lumbar paraspinal muscle, on axial T2 weighted MR scans, were investigated. Method 1 produced a discrete grey scale range for lean paraspinal muscle (0-120) that was applicable to the imaging set used in this study.

The results displayed in Figure 3.5 indicated that when using a discrete grey scale range, an error of 20 units at the upper end of lean muscle's grey scale range would result in a very small error in the measured muscle FCSA. Conversely, for this set of scans, if the upper limit of the muscle grey scale range is set below the 100 value the potential for error in determining the muscle FCSA would be far larger. Using a discrete grey scale range for muscle has the advantage of markedly reducing data processing time as once the discrete muscle grey scale range is established it is a simple process to apply it to the muscle CSA measurements in order to determine muscle FCSA.

The disadvantage of using a discrete grey scale range for muscle, in this case 0 – 120, is that the nature of MR means this grey scale range is unlikely to be precise for each muscle at every spinal level. This is because when using MR, even homogenous tissue types will have variable signal intensity within the same scan, within sets of scans for the same participant and within participants<sup>24</sup>. However, the results of this study indicate that the method the authors have used to determine a discrete grey scale range for muscle will produce only small variations in the muscle FCSA if the muscle grey scale range is slightly over-estimated or under-estimated. It should be noted that discrete grey scale ranges can probably only be used for this type of analysis with sets of scans obtained using identical MR protocols, systems and parameters. If there is large scan to scan variability in MR signal intensity of homogenous tissue types, then grey scale ranges for each tissue type should be determined for each scan slice, as per Method 2.

### 3.5.2 *Technique reliability*

The high ICC and low %SEM values relating to repeated measurement of CSA and FCSA clearly show that the technique described in this paper for examining the intramuscular morphology of the selected lumbar paraspinal muscles was highly reliable. The results of this study compare with those of Marras *et al.*<sup>29</sup> and Daneels *et al.*<sup>13</sup> who also found low variability

of repeated CSA measurements of similar groups of trunk muscles as seen on MR and CT scans respectively.

The significant negative correlation between mean FCSA and %SEM was probably due to a greater proportion of partial volume pixels at the smaller muscles' periphery being included in the FCSA. A slight difference in the outline of the CSA of the smaller muscles might therefore result in a relatively greater difference in muscle FCSA. The L4 multifidus was the most notable exception to this trend, as it has a relatively large FCSA and a relatively large %SEM. The fascial boundary between multifidus and the erector spinae was sometimes difficult to distinguish, particularly at the L4 level and this might explain the relatively high %SEM for the L4 multifidus.

The use of radiological techniques combined with image processing software to measure the CSA of muscles of the trunk is becoming increasingly prevalent in research pertaining to abnormalities in muscle morphology in LBP patients<sup>1, 2, 5, 15, 16, 30, 31</sup> and those interested in developing biomechanical models of the trunk<sup>29, 32, 33</sup>. The results of this study indicate that the methods described above to perform CSA measurements are highly reliable, especially when FCSA measurements are being made. This technique should facilitate further functional studies relating paraspinal muscle bulk and atrophy with symptoms and clinical outcomes in patients with LBP.

### 3.5.3 *Method application*

Addressing identified asymmetries in the morphology<sup>12, 13</sup> and deficits in function<sup>10</sup> of certain lumbar muscles has become a popular component of LBP rehabilitation programs<sup>1, 2, 4, 11</sup>. Recent developments in MR technology allow high-resolution images of muscles of the lumbar paraspinal muscles to be obtained without the risks associated with exposure to ionising radiation<sup>34</sup>. MR imaging has advantages over US imaging and CT in that MR allows better lean muscle to fat discrimination. Also, MR allows greater precision of repeat imaging over US, as

easily identifiable landmarks can be used to position the scan slices. MR therefore, appears to be an ideal imaging modality for assessing the intramuscular morphology of the lumbar paraspinal muscles. The method described in this paper would provide a valuable tool for assessing the efficacy of LBP rehabilitation programs.

A further application of determining muscle CSA area is in the area of musculoskeletal modelling. Accurate measurement of muscle CSA is important as anatomically detailed biomechanical models of the spine routinely use CSA measurements of the surrounding musculature to estimate variables related to injury. These variables include force production estimates of the lumbar paraspinal muscles and the associated compressive and shear force on structures such as the intervertebral discs and the partes interarticulares<sup>32, 33, 35, 36</sup>. Historically, much of the data pertaining to the geometry and morphology of spinal muscles for use in these models has been derived from cadaveric specimens<sup>25, 37</sup>. However, factors such as these participants' age, level of physical activity, race, sex and method of cadaveric preservation, may limit the application of such data within biomechanical models pertaining to populations such as healthy young athletes<sup>37</sup>. Also, in biomechanical models a mathematical expression that relates muscle CSA and isometric force production is used. The relationship is typically expressed as  $\text{Force} = K \times \text{physiological CSA}$ , where K is a constant that is approximately  $30\text{N}/\text{cm}^2$ <sup>32, 38, 39</sup>. A major assumption of this relationship is that the entire CSA consists of contractile tissue. There is evidence to suggest that paraspinal muscle atrophy with fat infiltration is associated with low back injury<sup>5, 15</sup>. This could result in muscle CSA being maintained but the percentage of contractile tissue within that CSA being markedly reduced. Also, in participants without LBP, the lower lumbar multifidi have been shown to have a greater amount of fat within the fascial boundaries when compared with the upper lumbar multifidi<sup>15</sup>. Therefore, functionally correct biomechanical models should utilise FCSA measurements obtained via a method such as that presented in this study.

This method of obtaining paraspinal muscle CSA and FCSA could also have application in the determination of segmental inertial parameters of the trunk, head and neck<sup>25,26</sup>. A method to determine the correct grey scale range for the MR signal emitted by various body tissues would increase the accuracy of these measurements.

A “gold standard” MR tissue segmentation method is currently not available. Therefore, a direct estimate of the validity of the methods used in this paper is impossible. Harris *et al.*<sup>17</sup> and Hoad and Martel<sup>18</sup> stated that manual methods of tissue classification were indeed the “gold standard” and in some automated applications, ROI of homogenous tissue are outlined in order to “train” the automated method<sup>17,23</sup>. The manual tissue segmentation techniques described in this paper were time consuming and somewhat subjective. The development of accurate and efficient automated tissue segmentation for MR images of skeletal muscle would greatly aid research of the relationship between lumbar muscle morphology, function and pain.

### **3.6 Conclusions**

It can be concluded within the limitations of this study that the method to determine muscle FCSA is both valid and highly reliable. The method of obtaining muscle CSA was highly reliable and the reliability indices were improved when FCSA was determined. Even if the upper limit of the grey scale range for the MR signal intensity of muscle is under-estimated or over-estimated, the effect on the muscle FCSA measurements was small. Further, the error in using a discrete grey scale range for MR signal intensity of lean paraspinal muscle was quantified. This method presented in this paper has several applications namely, evidence based LBP rehabilitation, biomechanical modelling and determination of segmental inertial parameters.

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## CHAPTER 4 - Study III

Cross-sectional area (CSA) asymmetries of certain lumbar paraspinal muscles, multifidus and psoas, have previously been associated with the occurrence of LBP amongst the general population. These asymmetries are thought to be a quantitative manifestation of lumbar paraspinal muscle dysfunction. A recent study associated the incidence of the most prevalent fast bowling low back injury diagnosis, non-dominant side lumbar stress fracture, with asymmetry of the quadratus lumborum muscle in a group of elite junior fast bowlers. The authors suggested that asymmetry of the quadratus lumborum muscle placed greater load on the non-dominant side L4 pars interarticularis predisposing it to stress injury. In contrast, a finite element modelling study by de Visser *et al.* (2006) indicated that quadratus lumborum asymmetry might help to reduce lumbar stress.

No study to date has investigated the morphology and symmetry of the lumbar paraspinal muscles in professional fast bowlers in cricket. This type of data *in-vivo* paraspinal muscle size data, specific to the population under investigation, is required for more accurate modelling of lumbar stress production

The general aim of this study was to examine and describe the functional CSA (FCSA) of the lumbar paraspinal muscles in fast bowlers in cricket compared with an active control group.

## **The lumbar paraspinal muscle morphometry of fast bowlers in cricket**

Adapted from: Ranson CA, Burnett AF, O'Sullivan PB, Batt ME, and Kerslake R. The lumbar paraspinal muscle morphometry of fast bowlers in cricket. *Clinical Journal of Sport Medicine*. 18:31-37, 2008.

### **4.1 Abstract**

The objective of this descriptive cross-sectional between-groups study was to describe the MRI functional cross sectional area (FCSA) of the lumbar paraspinal muscles of professional fast bowlers in cricket and to investigate the nature of any muscle asymmetry. The participants were 46 asymptomatic professional fast bowlers and 17 athletic controls. A relatively high percentage of fast bowlers had asymmetrically (greater than 10% difference in the FCSA between the dominant and non-dominant side muscles) larger dominant side quadratus lumborum FCSAs at L1 (47%) L3 (41%) and L4 (47%). The non-dominant side psoas FCSA was larger in fast bowlers at L5, and the dominant side multifidus FCSA was larger in both the fast bowlers at L3 to S1 and in the control subjects at L4 and L5. There was a higher prevalence of lumbar muscle asymmetry in the fast bowler group. Paraspinal muscle asymmetry was most prevalent in the quadratus lumborum of fast bowlers, and was also evident in the lumbar multifidus in both groups of subjects. In both muscle groups this was consistent with hypertrophy of the dominant side muscle. This study may be used to inform prospective studies of risk factors for low back injury in athletic males and enhance the development of more accurate models of stress production in the lumbar spine during fast bowling and other asymmetrical sports.

## 4.2 Introduction

Professional cricket is generally considered to have a low injury rate <sup>1</sup> however, the game's fast bowlers suffer from a high prevalence of lower back injury. Of these, stress fractures, typically of the non-dominant side lumbar posterior elements (pedicles and partes interarticales) <sup>2-5</sup> account for the most lost playing time <sup>1, 6</sup>. In previous studies there are many factors that have been related to back injury. The use of a 'mixed' bowling action, characterised by large counter rotation of the shoulders, is a technique factor that has been repeatedly associated with lower back injury in fast bowlers <sup>2, 7-9</sup>. Other risk factors for low back injury in fast bowlers include bowling at high speed <sup>10</sup>, having an extended knee when the front foot is in contact with the ground during delivery of the ball <sup>2</sup> and overuse <sup>9, 11, 12</sup>.

In addition to the risk factors listed above, a previous prospective study examining a group of elite junior fast bowlers reported a high prevalence of the dominant side quadratus lumborum muscle being significantly larger than the non-dominant side muscle <sup>13</sup>. Follow-up studies reported a strong relationship between quadratus lumborum volume asymmetry and increased incidence of lumbar stress injuries <sup>14, 15</sup>. Furthermore, it was suggested that asymmetry of the quadratus lumborum muscle placed greater load on the non-dominant side L4 pars interarticularis predisposing it to stress injury. In contrast, a recent finite element modelling study indicated that quadratus lumborum asymmetry might help to reduce lumbar stress <sup>16</sup>. The model used calculated pars interarticularis stress using both symmetrical and asymmetrical quadratus lumborum CSA measurements obtained from a general population computed tomography database. The authors of this, and another study <sup>17</sup> have commented that *in-vivo* paraspinal muscle sizes, specific to the population under investigation are required for more accurate modelling of lumbar stress production.

Asymmetry of other segmental stabilisers such as the lumbar multifidus and psoas has been associated with both acute and chronic low back pain (LBP) in the general population <sup>18-20</sup>. This asymmetry, presumably secondary to pain, may be due to neural inhibition that causes unisegmental atrophy of these muscles, ipsilateral to the side of pain <sup>20</sup>.

Further, there is evidence to suggest that segmental atrophy of the lumbar multifidus muscle after an acute episode of LBP does not spontaneously normalise once pain has resolved<sup>21</sup> and this has been suggested to be a contributing factor in the recurrence of LBP<sup>18, 21</sup>.

It has also been revealed that significant atrophy of specific lumbar paraspinal muscles can occur without a reduction in the total muscle CSA<sup>22, 23</sup>. These authors described paraspinal muscle atrophy in terms of replacement of muscle with fat and fibrous tissue, which would consequently result in reduced functional contractility of muscle. Therefore, a measure of the area of lean muscle tissue within a muscle's fascial boundaries (the functional cross-sectional area - FCSA) would be a better indicator of the muscle's contractile ability than total CSA which has been generally reported by investigators in this field<sup>24-27</sup>. Magnetic resonance imaging (MRI) is a non-invasive imaging modality that can be used to determine both muscle CSA and FCSA of the lumbar musculature<sup>28, 29</sup>.

Therefore, the aims of this study were to use MRI to examine the FCSA of the lumbar paraspinal muscles in currently asymptomatic professional senior fast bowlers and to investigate the prevalence and nature of any lumbar paraspinal muscle asymmetry. It was hypothesised that there would be a high prevalence of FCSA asymmetry of the paraspinal muscles of these fast bowlers when compared with a group of active controls whose activities don't involve significant levels of asymmetrical trunk motion.

## **4.3 Materials and Methods**

### **4.3.1 Subjects**

Forty-six male professional fast bowlers and 17 age-matched controls were recruited for this study. The mean ( $\pm$ SD) age, height and mass of the fast bowlers was 22 ( $\pm$ 3) years, 187 ( $\pm$ 5) cm and 84 ( $\pm$ 7) kg respectively. For the control subjects these were 25( $\pm$ 5) years, 182 ( $\pm$ 5) cm and 79 ( $\pm$ 12) kg respectively.



The bowlers were considered as fast bowlers by the England and Wales Cricket Board (ECB) fast bowling coaches and had bowled in matches or training sessions at least three days per week throughout the professional season. Whilst the bowlers had no reported LBP in the three months prior to the time of testing (end of the professional season), ECB injury surveillance data gathered between 1999-2006 <sup>6</sup> indicates that a high number of subjects have a history of low back injury (Table 4.1).

Table 4.1 The number and percentage of subjects with i) no lower back injury history, ii) history of acute lumbar stress fracture or iii) diagnoses of other lower back injury, and the average number of days missed per injury during the period 1999 to 2006.

Lower Back Injury History	Number (%) of Subjects	Average Days Missed per Injury
None	19 (40%)	-
Acute stress fracture	18 (37%)	129
Other lower back injury	11 (23%)	27

Inclusion criteria for the control subjects were that they participated in a minimum of two hours of physical activity, three times a week. The main physical activities of the control subjects were soccer (four subjects), backline players in amateur rugby (five subjects), gym based weightlifting and cardiovascular exercise (seven subjects), and swimming (one subject). Exclusion criteria for the control group were; previous low back injury resulting in the inability to participate in physical activity for greater than one week, previous low back surgery and regular participation in cricket or other predominantly one-sided sports e.g. racket sports, throwing sports. The dominant side in the fast bowlers was defined as their bowling arm side and the controls' dominant side was assigned to the arm they preferentially used to throw a ball. Forty-three (93%) fast bowlers and 16 (94%) controls were right side dominant.

#### 4.3.2 *Ethical considerations*

The subjects provided written informed consent to participate in the study and ethical approval for the study was provided by the Local Region Ethics Committee of the University of Nottingham, UK, and Curtin University of Technology, Western Australia.

#### 4.3.3 *Scanning protocol and image analysis*

Axial T2 MR scans of the subjects were taken at seven spinal levels; they being the lower vertebral end plate of L1 to L5 and the upper vertebral endplate of L5 and S1. Scans were obtained using a General Electric 1.5 Tesla MR scanner employing a fast spin echo sequence of TR 4000 ms, Teef 120 ms, 5mm slice thickness, 512 x 512 matrix. These muscles imaged were the left and right psoas major, quadratus lumborum, multifidus and the combined bulk of the erector spinae muscles, iliocostalis and longissimus. The iliocostalis and longissimus were grouped as their fascial boundaries were difficult to determine on some scans.

CSA measurements at each spinal level were determined by outlining the fascial boundary of the abovementioned muscles using Image J V1.36b software (National Institutes of Health, USA). FCSA measurements for each muscle were determined by thresholding the CSA to include only pixels that were within a previously determined grey scale range for the MR signal intensity of lean muscle tissue (Figure 4.1). This approach has been previously shown to be reliable and valid <sup>28</sup>. The quadratus lumborum and psoas muscles' FCSA could only be measured between the L1 to L4 and L2 to L5 spinal levels respectively as can be seen by the anatomical attachments for all muscles examined in this study (Chapter 1, Table 1.1).

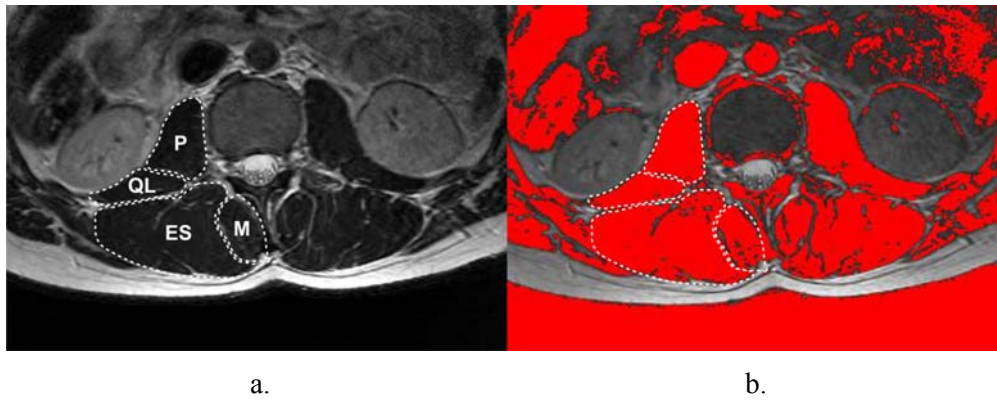


Figure 4.1 Axial MRI scan at the level of the inferior vertebral end-plate of L2 showing the regions of interest used to calculate a) the cross-sectional area and b) the functional cross-sectional area (red) of the lumbar paraspinal muscles; psoas (P), quadratus lumborum (QL), erector spinae (ES – combined longissimus and iliocostalis) and multifidus (M).

#### 4.3.4 Statistical analysis

Paired t-tests were used to determine if there were differences between the non-dominant and dominant side FCSA of each muscle, at each spinal level. Unpaired t-tests were used to determine whether there was any difference in the percentage difference in FCSA of dominant versus the non-dominant side muscle, at each spinal level, between the fast bowlers and the control subjects. Furthermore, FCSA measurements for each muscle, at each spinal level, were considered to be asymmetrical if there was a greater than 10% difference between the non-dominant and dominant side. This level was considered a biomechanically and clinically significant threshold of muscle asymmetry based on previous studies<sup>15, 20</sup>. At spinal levels where sufficient numbers of subjects with asymmetrical muscles occurred, chi-square tests were used to determine whether there was a difference in the prevalence of paraspinal muscle asymmetry between the fast bowlers and the control subjects. Statistical significance was set at  $p < 0.05$  and all statistical procedures were conducted using the Statistical Package for Social Sciences V14.0.

#### **4.4 Results**

Detailed data for non-dominant and dominant side FCSA (cm<sup>2</sup>) are shown in Table 4.3. The FCSA of the non-dominant side psoas was significantly larger than the dominant side at L5 superior (4.1%, p=0.003) and L5 inferior (3.9%, p=0.02) in the fast bowlers and at L2 (9%, p=0.02) in the control subjects. The dominant side quadratus lumborum FCSA was significantly larger at L1 (9%, p=0.003), L3 (4.5% p=0.003) and L4 (8.5% p=0.002) in the fast bowlers whilst there was no difference at any level in the controls. The dominant side erector spinae FCSA was significantly larger at L2 (4.5%, p<0.001) in the fast bowlers and at L3 in the controls (2.3%, p=0.04). The dominant side lumbar multifidii FCSA was significantly larger at L3 (4.8%, p=0.003), L4 (3.3%, p=0.04), L5 inferior (4.8%, p=0.001) and S1 (2.9%, p=0.01) in the fast bowlers and at L4 (5.3%, p=0.01) and L5 superior (6.9%, p=0.02) and L5 inferior (7.4%, p=0.002) in the control subjects.

Table 4.2 Percentage difference (%Diff) in the Functional cross-sectional area (SD) (cm<sup>2</sup>) of the dominant (Dom) and non-dominant (ND) side lumbar paraspinal muscles in fast bowlers (n=46) and control subjects (n=17).

Spinal Level	Bowlers	Psoas			Quadratus Lumborum			Erector Spinae			Multifidus		
	Controls	Dom	ND	%Diff	Dom	ND	%Diff	Dom	ND	%Diff	Dom	ND	%Diff
L1	Mean (SD)	*	*	*	<b>4.1</b> (1.1)	<b>3.7</b> (1.1)	<b>9.1</b> (20.7)	23.9 (4.0)	23.9 (4.3)	0 (7.0)	3.8 (1.2)	3.7 (1)	2 (13.3)
	Mean (SD)	*	*	*	4 (0.9)	4.1 (0.80)	<b>-4.4</b> (14.5)	21.8 (3.2)	22 (2.5)	-1.7 ( 6.8)	3.8 (0.7)	3.7 (0.6)	1.2 (8.6)
L2	Mean (SD)	11.2 (2)	11 (0.8)	<b>0.6</b> (12.7)	6.6 (1.5)	6.4 (1.4)	2.1 (18.7)	<b>25</b> (4.6)	<b>23.7</b> (4.1)	4.5 ( 9.4)	5.1 (1.4)	5 (1.2)	1.3 (14.4)
	Mean (SD)	<b>8.7</b> (2.8)	<b>9.4</b> (9.0)	<b>-9</b> (14.2)	6 (1.2)	6.2 (1.1)	-4.8 (17.4)	23 (3.6)	22.6 (3.3)	1.4 ( 7.8)	4.5 (0.9)	4.7 (1.1)	-4.2 (14.7)
L3	Mean (SD)	17.7 (2.7)	17.3 (2.6)	1.6 ( 8.8)	<b>8.9</b> (2.3)	<b>8.3</b> (1.7)	4.5 (16.9)	21.1 (4.9)	21.2 (4.6)	-1.9 (12.6)	<b>9.9</b> (3.4)	<b>9.3</b> (3.2)	4.8 (13.4)
	Mean (SD)	14.6 (3.5)	15.2 (3.1)	-5.9 (15.7)	7.7 (1.9)	7.5 (1.4)	0.1 (22.7)	<b>20.5</b> (3.1)	<b>20</b> (3)	2.3 (4.5)	7.5 (2.1)	7.3 (2.1)	1.8 (13.6)
L4	Mean (SD)	23.5 (3.0)	24 (3.4)	-2.1 (8.0)	<b>9.5</b> (2.7)	<b>8.6</b> (2.6)	8.5 (19.4)	17.7 (3.3)	18.1 (3.4)	-3.5 (13.6)	<b>12.5</b> (3.3)	<b>12</b> (3.5)	3.3 (11.0)
	Mean (SD)	20.4 (3.7)	20.7 (3.5)	-1.9 (9.2)	7.8 (1.8)	7.9 (1.9)	-4.1 (27.1)	16.5 (2.9)	17.2 (3.3)	-4.4 (8.7)	<b>10.1</b> (2)	<b>9.5</b> (1.7)	5.3 ( 9.7)
L5 Sup	Mean (SD)	<b>24</b> (3.7)	<b>24.9</b> (4.1)	-4.1 (8.4 )	*	*	*	15 (3.7)	14.9 (3.8)	-0.5 (15.9)	12.4 (3.3)	12.4 (3.7)	-1 (23.3)
	Mean (SD)	22.1 (3.6)	22.1 (3.6)	-0.3 (7.2)	*	*	*	13.1 (2.5)	13.2 (2.4)	-2.3 (15.4)	<b>11.2</b> (2.1)	<b>10.3</b> (1.9)	6.9 (11.6)
L5 Inf	Mean (SD)	<b>22.2</b> (4.5)	<b>23</b> (4.8)	<b>-3.9</b> (10.9)	*	*	*	*	*	*	<b>13.1</b> (3)	<b>12.3</b> (2.6)	4.8 (11.0)
	Mean (SD)	20.5 (4.0)	19.6 (4.6)	<b>4.8</b> (8.4)	*	*	*	*	*	*	<b>11.7</b> (2.3)	<b>10.8</b> (1.8)	7.4 (8.4)
S1	Mean (SD)	*	*	*	*	*	*	*	*	*	<b>12.1</b> (2.9)	<b>11.7</b> (2.4)	2.9 (9.0 )
	Mean (SD)	*	*	*	*	*	*	*	*	*	11 (2)	10.5 (1.4)	2.9 (11.6)

\*muscle not seen at this level. **Bold numbers** in the Dom and ND columns indicate a significant side to side difference (p<0.05) in that muscle's FCSA.

**Bold numbers** in the %Diff columns indicates a significant difference between the Dom and ND side FCSA in the fast bowlers versus controls subjects.

Table 4.3 Number and percentage of fast bowlers and control subjects with symmetrical (<10% side to side difference in functional cross-sectional area) and asymmetrical (>10% side to side difference) functional cross-sectional area of the lumbar paraspinal muscles; Psoas, Quadratus Lumborum, Erector Spinae and Multifidus.

Spinal level	Group	Psoas			Quadratus Lumborum			Erector Spinae			Multifidus		
		Dom >10% larger	Within $\pm$ 10%	Non-dom >10% larger	Dom >10% larger	Within $\pm$ 10%	Non-dom >10% larger	Dom >10% larger	Within $\pm$ 10%	Non-dom >10% larger	Dom >10% larger	Within $\pm$ 10%	Non-dom >10% larger
L1	Bowlers	*	*	*	<b>21 (47%)</b>	<b>18 (40%)</b>	<b>6 (13%)</b>	2 (4%)	38 (84%)	5 (11%)	14 (31%)	24 (53%)	7 (16%)
	Controls	*	*	*	<b>2 (12%)</b>	<b>9 (53%)</b>	<b>6 (35%)</b>	1 (6%)	15 (88%)	1 (6%)	4 (24%)	12 (71%)	1 (6%)
L2	Bowlers	14 (30%)	21 (46%)	11 (24%)	14 (30%)	18 (39%)	14 (30%)	10 (22%)	32 (70%)	4 (9%)	14 (30%)	21 (46%)	11 (24%)
	Controls	1 (6%)	10 (59%)	6 (35%)	4 (24%)	8 (47%)	5 (29%)	2 (12%)	14 (82%)	1 (6%)	3 (18%)	6 (41%)	7 (41%)
L3	Bowlers	8 (17%)	34 (74%)	4 (9%)	19 (41%)	17 (37%)	10 (22%)	<b>7 (15%)</b>	<b>27 (59%)</b>	<b>12 (26%)</b>	16 (35%)	24 (52%)	6 (13%)
	Controls	1 (6%)	12 (71%)	4 (24%)	5 (29%)	7 (41%)	5 (29%)	<b>1 (6%)</b>	<b>16 (94%)</b>	<b>0</b>	4 (24%)	11 (65%)	2 (12%)
L4	Bowlers	2 (4%)	38 (83%)	6 (13%)	21 (47%)	17 (38%)	7 (16%)	4 (9%)	27 (59%)	15 (33%)	13 (28%)	27 (59%)	6 (13%)
	Controls	0	15 (88%)	2 (12%)	7 (41%)	4 (24%)	6 (35%)	1 (6%)	11 (65%)	5 (29%)	5 (29%)	11 (65%)	1 (6%)
L5 Superior	Bowlers	2 (4%)	33 (72%)	11 (24%)	*	*	*	13 (28%)	20 (44%)	13 (28%)	8 (18%)	31 (69%)	6 (13%)
	Controls	0	16 (94%)	1 (6%)	*	*	*	4 (24%)	8 (47%)	5 (29%)	6 (35%)	11 (65%)	0
L5 Inferior	Bowlers	4 (9%)	31 (67%)	11 (24%)	*	*	*	*	*	*	14 (30%)	28 (61%)	4 (9%)
	Controls	3 (18%)	13 (77%)	1 (6%)	*	*	*	*	*	*	7 (41%)	10 (59%)	0
S1	Bowlers	*	*	*	*	*	*	*	*	*	9 (20%)	35 (76%)	2 (4%)
	Controls	*	*	*	*	*	*	*	*	*	4 (25%)	10 (63%)	2 (13%)

**Bold numbers** indicate a significant difference in the prevalence of paraspinal muscle asymmetry between the fast bowlers and the control subjects.

# insufficient numbers to do a chi-squared test. \* muscle not seen at this level

## 4.5 Discussion

Of the four paraspinal muscles investigated, the quadratus lumborum of the fast bowlers and the lumbar multifidus in both the fast bowlers and controls showed the most striking asymmetry. Engstrom *et al.*<sup>15</sup> reported that subjects with a pre-existing quadratus lumborum muscle volume asymmetry (greater than 10%) were found to have a higher relative risk of pars interarticularis injury<sup>15</sup>. Conversely, hypertrophy of the dominant side quadratus lumborum might be secondary to a protective function of the dominant side acting to control the large trunk side-flexion moment<sup>30</sup>, thereby reducing stress on contralateral side of the lumbar spine during the delivery stride of fast bowling<sup>16</sup>.

Quadratus lumborum is a powerful side-flexor of the lumbar spine and is also thought to have a significant role in frontal plane segmental stabilisation during contralateral leg loading as well as during spinal movement<sup>30,31</sup>. During the front foot contact phase of the delivery stride of fast bowling the lower trunk attains a position of extreme side flexion to the non-dominant (non-bowling arm) side<sup>32</sup>. Whilst in this posture it is likely that the dominant side quadratus lumborum acts strongly, both to eccentrically control this extreme trunk contralateral side flexion and to isometrically control ipsilateral pelvic frontal plane posture i.e. the Trendelenburg sign<sup>30</sup>. Hypertrophy, secondary to repeated eccentric and isometric overload<sup>13,18</sup>, could contribute to the finding of the dominant side quadratus lumborum FCSA being significantly larger at multiple lumbar levels in the fast bowlers. A potential relationship between the degree of trunk side-flexion during fast bowling and the degree of quadratus lumborum asymmetry requires further study.

Quadratus lumborum muscle CSA has been found to be slightly larger in soccer players compared with weight lifters, distance runners and shooters although, whether this difference was considered symmetrical was not reported<sup>33</sup>. Raty and co-workers also found a significant

positive correlation between trunk flexion and side-flexion strength and quadratus lumborum CSA. Of these four groups of athletes, soccer players would perform the most dynamic, multidirectional trunk and limb movements. The findings of this study support the suggestion that the stabilising function of quadratus lumborum causes it to hypertrophy asymmetrically<sup>15</sup> as this was the case in a high proportion of the fast bowlers but also, to a lesser extent, in the athletic control subjects. Fast bowling, in particular, is an activity that involves repeated, dynamic, multidirectional trunk and limb movements, particularly asymmetrical trunk side-flexion and rotation<sup>32</sup>, that is likely to require high levels of asymmetric activation of the quadratus lumborum.

There was also a relatively high prevalence of lumbar multifidus FCSA asymmetry (>10%) in the fast bowlers, with the larger FCSA predominantly found on the dominant side. However, there was no difference in the percentage differences between the dominant and non-dominant side multifidus FCSA between the bowlers and the controls. Within the fast bowlers, the explanation for this finding is likely to be similar to that for the quadratus lumborum i.e. dominant side muscles eccentrically controlling large amounts of trunk flexion and contralateral side flexion<sup>32</sup>.

The presence of significantly larger dominant side lumbar multifidii at L4 and L5 in the athletic controls might also be due to dominant side hypertrophy due to preferential recruitment during predominantly dominant side dynamic limb motion<sup>34</sup>. Similarly, a larger non-dominant side psoas muscle FCSA at L5 in the fast bowlers also suggests fast bowling related hypertrophy of that muscle. It is likely that the non-dominant psoas would work concentrically with reversed origin to insertion to initiate the powerful lumbo-pelvic flexion and side flexion<sup>35</sup> that occurs during the front foot contact to ball release phase of the fast bowling<sup>32,36</sup>. The co-existing hypertrophy of the dominant side quadratus lumborum and multifidus and the non-dominant side psoas may reflect a muscle synergy across a motion segment controlling the asymmetrical trunk



motion of fast bowling. Psoas is known to flex the spine on the pelvis and also has the potential to generate high compressive and anterior shear forces in the lower lumbar spine due to a 'bowstring' effect when aligned across the lordosis during extended lumbar postures<sup>35</sup>. This is the predominant body posture during the start of the front foot contact phase of the delivery stride of fast bowling<sup>32, 36</sup>. The action of psoas on the non-dominant side, antero-lateral to the spine, would probably be counter-balanced by the dominant side quadratus lumborum and multifidii located on the dominant, postero-lateral side of the spine. Whilst controlling movement, these muscle synergies would also impose large compressive and shear loads<sup>35</sup> on the adjacent non-dominant side lower lumbar spine which could in turn, contribute to the aetiology of the bony stress lesions highly prevalent in fast bowlers. However, finite element modelling studies are required to accurately estimate the relative influence of asymmetrical development of the paraspinal muscles in the aetiology of lumbar stress injuries typical of fast bowlers, or whether lumbar muscle asymmetry is simply an adaptive consequence of the complex lumbar kinematics of the fast bowling delivery stride.

There was some segmental variation in the degree of paraspinal muscle asymmetry (Table 4.3). However, only psoas and multifidus in the control subjects had more than a 10% variation in asymmetry across all levels. Possible reasons for segmental variation in FCSA include; small inherent measurement errors<sup>28</sup>, normal segmental variation in the attachment, morphology and location of the paraspinal muscles (Table 4.2), variability in the lower back pain history particularly in the fast bowling group (Table 4.1)<sup>20</sup> and, variability of the exercise and activity profiles of the subjects which may have influenced regional muscle development.

Along with the paraspinal muscles examined in this study, the muscles of the abdominal wall; rectus abdominus, the external and internal obliques and the transversus abdominus, are known to have a significant role in the production and control of lower trunk motion<sup>31, 34, 37</sup>.

Although not able to be examined in this study, the specific morphometry of these muscles should also be investigated in future research.

Paraspinal muscle CSA/FCSA data is required for modelling spinal mechanics and pathomechanics. However, muscle CSA data obtained from studies of cadavers, or the general population, may not be valid for use in modelling the mechanics of specific sporting activities<sup>17</sup>. The FCSA data obtained in this study may assist in developing models of lumbar spine stresses in male fast bowlers<sup>16</sup> and other sports of a unilateral/asymmetrical nature which are known to have high rates of low back injury e.g. tennis, javelin and sweep rowing. In addition, the results of this study may be used to guide future prospective studies that wish to examine the relationship between paraspinal muscle asymmetry and the prevalence and pattern of lower back injury in fast bowlers. Further research is also required to determine whether the pattern of fast bowler paraspinal muscle morphometry identified in this, and other studies<sup>13, 14</sup>, contributes to<sup>15</sup>, or assists in protecting athletes from lumbar stress injuries<sup>16</sup>. Regardless, identification of the trunk kinematics associated with paraspinal muscle development may then play an important role in developing coaching and exercise programmes aimed at addressing potentially dangerous muscle asymmetries and/or bowling technique characteristics.

The current study has some limitations. Firstly, our findings should be interpreted cautiously as multiple statistical comparisons were made which although not inappropriate<sup>38</sup>, increases the probability of significant results by chance<sup>39</sup>. Secondly, direct muscle size comparisons between the fast bowling and control subjects were not made. From examining the descriptive data from psoas there may be a possibility of difference in muscle size between bowlers and controls. However, this was not attempted as normalising the FCSA measurements for body size to allow this comparison may cloud the descriptive data and diminish its usefulness for subsequent studies. Thirdly, the relationship between paraspinal muscle FCSA asymmetry

and lower back injury history was not directly examined as all subjects were pain free at time of MR scanning.

#### **4.6 Conclusions**

Paraspinal muscle asymmetry was most prevalent in the quadratus lumborum of fast bowlers and was consistent with hypertrophy of the dominant side muscle. The dominant side multifidus in both the fast bowlers and controls and the non-dominant side psoas in the fast bowlers also had a tendency to be asymmetrically larger. The association between the pattern of paraspinal muscle asymmetries identified in this study and the aetiology and prevention of lower back injuries in fast bowlers in cricket requires further investigation. The data presented in this study may aid that process by informing prospective studies of low back injury risk factors and by allowing the development of more accurate models of stress production in the lumbar spine during fast bowling.

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## **CHAPTER 5 - Study IV**

Earlier studies have used measurements of the alignment of the pelvis and shoulders, in the transverse plane, to classify bowling actions into 4 types: Front-On (FO), Side-On (SO), Semi-open, and Mixed. The Mixed action type has been associated with increased risk of low back injuries such as lumbar stress fractures. Although associated with increased risk of lumbar stress fractures, excessive counter rotation is unlikely to be the direct pathomechanical cause of this type of injury. Only one previous study, using an electromagnetic device, has investigated the 3D kinematics of the lower trunk during fast bowling, whereas no study has investigated the 3D kinematics of the lower trunk using modern motion analysis techniques in a large group of professional fast bowlers.

The aims of this study were to describe the 3D kinematics of lower trunk during fast bowling and to investigate the relationship between the movements most likely to induce stress in the non-dominant side lumbar spine i.e. lower trunk extension, contralateral side-flexion and ipsilateral rotation and the various bowling action types. The investigation may lead to a better understanding of the likely pathomechanics and technique characteristics of low back injuries in fast bowlers.

## **The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket.**

Adapted from: Ranson C, Burnett A, King M, Patel N, and O'Sullivan P. The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *Journal of Sports Sciences*. 26:267-276, 2008.

### **5.1 Abstract**

Lower back injuries, specifically lumbar stress fractures, account for the most lost playing time in professional cricket. The aims of this study were to quantify the proportion of lower trunk motion utilised during the delivery stride of fast bowling and to investigate the relationship between the current fast bowling action classification system and potentially injurious kinematics of the lower trunk. Three-dimensional kinematic data were collected from 50 male professional fast bowlers during a standing active range of motion trial and three fast bowling trials. A high percentage of the fast bowlers used a mixed bowling action attributable to having shoulder counter-rotation greater than 30°. The greatest proportion of lower trunk extension (26%), contralateral side-flexion (129%) and ipsilateral rotation (79%) was utilised during the front foot contact phase of the fast bowling delivery stride. There was no significant difference in the proportion of available lower trunk extension, contralateral side-flexion and ipsilateral rotation range of motion used during fast bowling by mixed and non-mixed action bowlers. Motion of the lower trunk, particularly side-flexion, during front foot contact, in addition to variables previously known to be related to back injury e.g. shoulder counter-rotation, should be examined in future cross-sectional and prospective studies examining fast bowling action and low back injury.

## 5.2 Introduction

Lower back injuries to fast bowlers in cricket results in the greatest amount of lost playing time amongst professional cricketers<sup>1,2</sup>. Lumbar stress injuries (pedicle or pars interarticularis stress reaction and stress fracture) are the most prevalent injury type and in fast bowlers these occur predominantly on the opposite side to the bowling arm<sup>3-6</sup>. In addition, a unique pattern of multi-level, non-dominant side, chronic partes interarticulares stress reactions are highly prevalent in this population, and compared with age-matched athletic individuals, fast bowlers have a higher prevalence of multiple level lumbar disc degeneration<sup>6</sup>.

Several studies published since the late 1980's have identified and examined risk factors for lower back injury and lumbar radiological abnormalities commonly seen in fast bowlers<sup>3, 7-13</sup>. It is believed that the development of lower back injury in fast bowlers is multifactorial, however fast bowling technique has been the predominant area of investigation due to the reported relationship between specific aspects of fast bowling technique and the appearance of radiological abnormalities of the lower back<sup>3, 9, 11</sup>.

The fast bowling action takes place during what is known as the delivery stride. The first critical event during the delivery stride is back foot impact which marks the commencement of the back foot contact phase. This is followed by front foot impact, at the start of the front foot contact phase, then ball release. Fast bowling actions can be broadly categorised into one of four action types: front-on, side-on, mid-way and mixed and this is determined according to the alignment of the shoulders at back foot contact and the amount of shoulder counter-rotation during the delivery stride<sup>3, 10, 13, 14</sup>. Shoulder counter-rotation has been typically defined as the change in the shoulder alignment angle from back foot contact (Figure 5.1a) to the most side-on shoulder alignment (Figure 5.1c) during the delivery stride (minimum shoulder angle).

Several classification systems have been described in the literature with shoulder counter-rotation thresholds for the mixed action being as low as 10°<sup>3, 15</sup> and as high as 40°<sup>8</sup>.

One reason for the large difference in these thresholds might be that previous investigators may have determined shoulder alignment at differing instants of the back foot contact phase of the delivery stride<sup>13</sup>. Unfortunately, this is difficult to evaluate as previous authors have not provided detail pertaining to the precise instant at which shoulder alignment angles were collected<sup>8, 10-13, 15-17</sup>. However, the fast bowling classification systems most commonly in use within the cricket associations in the United Kingdom and Australia state that any bowler that has greater than 30° shoulder counter-rotation is classified as having a mixed action<sup>13, 14</sup>. Further, when measuring shoulder and pelvic alignment, bowlers can be classified as having a mixed action when the back foot contact pelvic to shoulder separation angle exceeds 30°<sup>10, 13, 17</sup>.

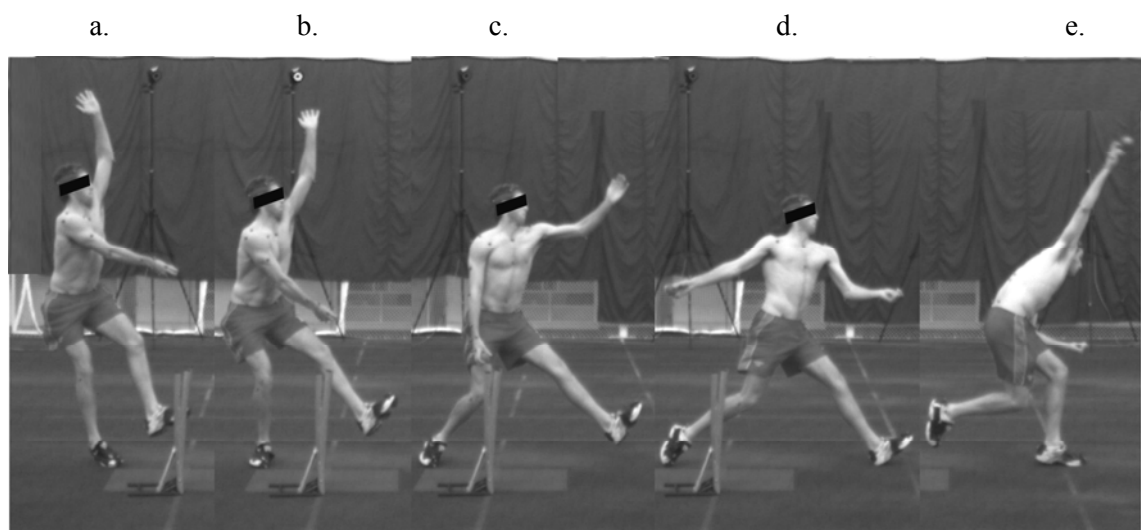


Figure 5.1 The delivery stride of fast bowling a) Back foot impact b) Back foot flat c) Minimum shoulder angle d) Front foot impact e) Ball release.

Several studies have reported an association between lower back injury and the mixed bowling action<sup>3, 8, 9, 11</sup>. Specifically, Portus and co-workers<sup>13</sup> in a retrospective study of elite Australian fast bowlers, reported that bowlers who previously suffered lower back soft tissue injuries had non-significantly larger back foot contact pelvic to shoulder

separation angles. Furthermore, shoulder counter-rotation values were found to be significantly higher in bowlers who had suffered lumbar stress fractures when compared with non trunk-injured bowlers. However, the precise mechanism behind the relationship between high shoulder counter-rotation and elevated rates of lumbar spine stress in mixed action bowlers is presently unknown. It has been previously speculated that the combined postures of lumbar extension, contralateral side-flexion and ipsilateral rotation adopted by fast bowlers during the front foot contact phase of the delivery stride, are likely to be directly involved in the pathomechanics lower back stress injuries<sup>8, 13, 18</sup>. However, due to problems such as the unavailability and cost of suitable motion analysis technology, previous investigators were not readily able to quantify the true three dimensional (3D) motion of the lower trunk.

To date, only one study<sup>16</sup> which examined a group of junior elite fast bowlers, has investigated aspects of the 3D kinematics of the lower trunk during fast bowling. This study revealed that although variables used to classify fast bowling action type occurred between back foot impact and front foot impact, the movements most likely to place the greatest mechanical load on the lumbar spine occurred between front foot impact and ball release. Coincidentally, this is also the phase of the bowling action where peak ground reaction forces are produced<sup>7, 8, 19</sup>.

Chosa and colleagues<sup>20</sup> found that unilateral pars interarticularis stress was 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. Further, it is known that the available range of motion of lumbar axial rotation is reduced when the spine is in end range extension when compared with a neutral posture<sup>21, 22</sup>, therefore implying increased stiffening of the spine when it is positioned near the limits of its physiological range of motion. Panjabi<sup>23</sup> terms this zone of high stiffness towards end range the “elastic zone of motion”. Repeated motion within this “elastic zone”, combined with the

large ground reaction forces during front foot contact, may well provide the pathomechanical forces responsible for the unique pattern of contralateral side lower lumbar stress injuries.

Therefore, the aim of this study was to quantify the proportion of lower trunk extension, side-flexion and axial rotation utilised during the delivery stride of fast bowling. This was examined in a group of senior professional players. A secondary aim was to investigate the relationship between the current fast bowling action classification system and potentially injurious kinematics of the trunk during fast bowling. Kinematic variables included those used to classify bowling action type i.e. shoulder alignment and shoulder counter-rotation, along with the 3D kinematics of the lower trunk throughout the delivery stride of fast bowling.

## **5.3 Methods**

### *5.3.1 Participants and experimental protocol*

This study recruited 50 professional male fast bowlers from English County Cricket clubs. This sample represented approximately 25% of the professional fast bowlers playing first class County Cricket. Participants were considered as fast bowlers by the England Cricket Board fast bowling coaches. The mean ( $\pm$  s) age, height and mass of the participants was  $23 \pm 4$  years,  $1.86 \pm 0.05$ m and  $86 \pm 8$ kg respectively. Participants were deemed fit to bowl by their County Physiotherapist and had all bowled three times per week, on average, in either practice sessions or matches during the current season. Ethical approval for this study was obtained from the Human Research Ethics Committees of the University of Nottingham, UK and Curtin University of Technology, Western Australia.

### *5.3.2 Data collection*

A 12 camera Vicon Motion Analysis System (Oxford, UK) operating at 120 Hz was used to capture a lower trunk range of motion trial and six fast bowling trials for each bowler. These trials were maximum velocity deliveries that pitched in an area designated as

a good line and length by a qualified fast bowling coach. Testing was conducted in the indoor practice facility at the England and Wales Cricket Board National Cricket Centre at Loughborough University. This facility allowed the participants to bowl with their normal length run-up on a standard size artificial cricket pitch (Figure 5.2). Cameras were positioned around the bowling crease to cover a  $7\text{m} \times 3\text{m} \times 3\text{m}$  volume which was wand calibrated prior to data collection.



Figure 5.2 Experimental setup in the indoor cricket training facility.

Thirty-one, 14mm diameter spherical reflective markers were attached to bony landmarks (standard Vicon Golem whole body marker set, OMG Plc, Oxford UK) using aerosol sports adhesive and double-sided tape. Seven of these markers were used to define two local reference frames in the pelvic and lower thorax regions of the trunk:

- Pelvic reference frame – markers were placed over the left and right anterior superior iliac spine (ASIS) and the left and right posterior superior iliac spine (PSIS).

- Lower thorax reference frame – markers were placed over the xiphoid process at the distal end of the sternum and the spinous processes of T10 and L1.

The pelvic and lower thorax reference frames were used to quantify lower trunk kinematics during the range of motion and fast bowling trials.

Markers were also attached to the right and left acromia, the head (four), arms (four on each arm) and legs (four on each leg) to allow whole body motion to be determined using Vicon BodyBuilder (OMG Plc, Oxford UK) software. A square of reflective tape (2cm × 2cm) was also fixed to one side of the cricket ball to allow the instant of ball release and the ball velocity to be determined. Prior to testing participants were given adequate time for their routine pre-bowling warm-up activities which included several warm-up deliveries.

For the standing range of motion trial the bowlers were given a demonstration and instruction in how to move to their end range of active lower trunk flexion and extension, left and right side-flexion, and left and right axial rotation. The instructions were: “From an upright standing position, with your arms held out horizontally to the side, bend as far as you can forwards, then as far as you can backwards. Then, again starting from the upright position, bend over as far as you can to the left, then to the right. Finally, move back to upright and rotate as far as you can to the left, then to the right.” Participants were also instructed to keep their legs straight throughout the manoeuvres and to maintain a static pelvic position whilst side flexing and rotating their trunk. Participants then practised each motion so that the investigators were confident they maintained the correct posture and were moving to the end of their trunk range of motion in each direction.

### 5.3.3 *Data processing*

Three-dimensional marker locations were reconstructed using the Vicon Workstation (OMG Plc, Oxford UK) software and all six bowling trials were manually



labelled before selecting the best three (maximum velocity trials with minimal marker loss) of each bowler for further analysis along with the range of motion trial.

Determining the two local reference frames which defined lower trunk kinematics required an origin and two vectors to be defined for each coordinate system. Both reference frames were defined with the first axis equal to vector 1, the second axis equal to the cross-product of vector 2 and vector 1 and the third axis equal to the cross-product of the first and second axes such that a right handed orthogonal reference frame was produced with the X axis defined as the lateral axis, the Y axis as the frontal axis and the Z axis as the longitudinal axis (Figure 5.3).

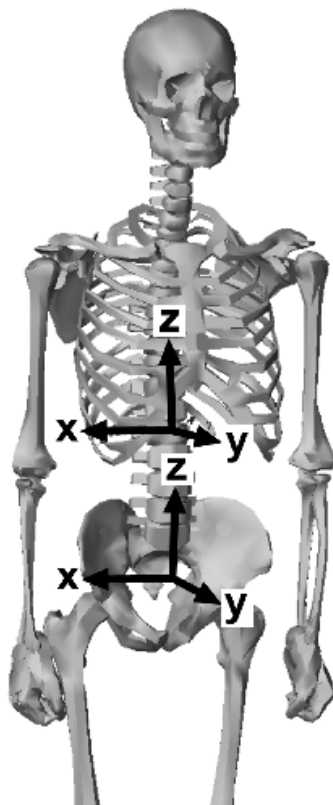


Figure 5.3 Local orthogonal reference frames for the pelvis and lower thorax used to determine lower trunk kinematics.

The time histories of each kinematic descriptor were fitted using quintic splines <sup>24</sup>. The closeness of fit at each point was based on the difference between the descriptor value and the average value from the two adjacent times <sup>25</sup>.

#### 5.3.4 *Bowling action classification*

Most of the previous studies that have classified bowling actions according to shoulder, or shoulder and pelvic alignment have viewed these segments in the horizontal plane <sup>10, 13, 17</sup>. Consequently, in the current study the shoulder angle was determined by projecting the 3D alignment of the left and right acromia onto a horizontal plane (180° = side-on, 270° = shoulders aligned with the bowling crease).

In this study, only shoulder angle, at two instances of back foot contact, and the magnitude of shoulder counter-rotation were used to classify the type of bowling action utilised as the third variable used to classify action type; pelvic to shoulder separation at back foot impact (Table 5.1), has been shown not to be associated with lumbar posterior element stress injury in fast bowlers <sup>13</sup>. In order to explore the effect of using different back foot contact instants on the calculation of variables such as shoulder counter-rotation, the shoulder angle was measured at two instances in the back foot contact phase of the delivery stride. These instants were based upon visual inspection of the horizontal time histories of the heel and toe markers and were defined as follows:

- Back foot impact - the first image in which any part of the back foot came in contact with ground.
- Back foot flat - the first image during the back foot contact phase of the delivery stride in which the greatest proportion of the sole of the foot was in contact with ground.

Table 5.1 Fast bowling action classification variables and their typical values used to define fast bowling action types <sup>13</sup>.

Action Type	Back Foot Contact Shoulder Angle	Shoulder Counter-Rotation	Back Foot Contact Pelvic-Shoulder Separation
Front-on	>240°	<30°	<30°
Midway	240° - 210°	<30°	<30°
Side-on	<210°	<30°	<30°
Mixed	n/a	≥30°	≥30°

#### 5.3.5 Lower trunk kinematics

The orientation of the lower thorax reference frame relative to the pelvic reference frame was defined using Cardan angles to quantify flexion-extension about a lateral pelvic axis, side-flexion about a floating frontal axis, and axial rotation about the lower thorax longitudinal axis for both the range of motion and bowling trials <sup>16, 26</sup>. A ‘neutral’ upright anatomical position was identified for each bowler in the range of motion trial and all subsequent measures were then expressed relative to this posture. As the absolute angular position about each orthopaedic axes for the lower trunk relative to the pelvic reference frame in the standing neutral posture was not equal to zero, matrix algebra procedures outlined by Burnett *et al.* (1998) were used to adjust the neutral posture to (0, 0, 0). Maximal lower trunk motion of the variables thought most likely to contribute to contralateral side lumbar stress injuries i.e. extension, contralateral side-flexion and ipsilateral axial rotation, <sup>20</sup> were determined for the range of motion trial, and each bowling trial.

#### 5.3.6 Reliability of the kinematic variables

Intra-class correlation, and relative standard error of measurement statistics <sup>27</sup> were calculated to determine the inter-trial variability of each of the variables used to determine the bowling action type (using both back foot contact phase instants; back foot impact and

back foot flat), and each of the lower trunk kinematic variables obtained during the three fast bowling trials. To further quantify the inter-trial variability and the random noise in the data, average standard deviation and standard error of the mean values were calculated for each variable, for each participant, using both BFI and back foot flat.

All action classification and trunk kinematic variables had high intra-class correlation values (range 0.86 - 0.97) (Table 5.2). Low relative standard error of measurement values were found for all variables (range 1.5 - 9.1) apart from, shoulder counter-rotation (calculated using the back foot flat instant) and lower trunk extension which had moderate relative standard error of measurement values (13.4 & 17.2 respectively) (Table 5.2). In addition, the overall average standard deviation for all action classification and trunk kinematic variables was low (2.8°, range 1.8° - 5°), as was the overall average standard error of the mean (1.6°, range 1.1° - 2.9°). Consequently, data from three trials for each dependent variable in the study were averaged to provide representative values for each bowler. The maximum lower trunk extension, contralateral side-flexion and ipsilateral rotation utilised during the fast bowling trials was then expressed as a percentage of the maximum range of motion achieved during the range of motion trial.

Table 5.2 Reliability indices, intra-class correlation (ICC) and relative standard error of measurement (%SEM), for variables used to determine fast bowling action type and trunk kinematic variables of interest. Action classification variables are calculated using two back foot contact shoulder alignment instants; back foot impact (BFI) and back foot flat (BFF). All mean (s) data are in degrees.

Kinematics	Variable	Mean° (s)	ICC	%SEM
Action Classification	Shoulder Angle - BFI	234 (18)	0.97	1.5
	Shoulder Angle - BFF	227 (18)	0.93	2.0
	Minimum Shoulder Angle	194 (10)	0.90	1.5
	Shoulder Counter-Rotation - BFI	41 (16)	0.97	6.7
	Shoulder Counter-Rotation - BFF	34 (15)	0.91	13.4
Lower Trunk Kinematics	Extension	9 (6)	0.93	17.2
	Contralateral Side-Flexion	34 (7)	0.88	6.7
	Ipsilateral Rotation	32 (8)	0.86	9.1

The instants of the delivery stride where bowlers obtained the minimum shoulder angle, maximum lower trunk extension, maximum contralateral side-flexion and maximum ipsilateral rotation, relative to the time of front foot impact, were also determined.

### 5.3.7 Statistical analysis

Independent t-tests were used to determine if there was any difference in the proportion of lower trunk range of motion utilised by mixed and non-mixed action (front-on, midway and side-on) bowlers classified using both the back foot impact and back foot flat definitions of back foot contact. Non-mixed action bowlers were pooled as these action types have previously been considered ‘safer’ for the lower back than the mixed action<sup>8, 11, 12, 16</sup>. Effect sizes were also calculated for this comparison with effect sizes of 0.2 to 0.5 considered small, 0.5 to 0.8 medium and above 0.8 large<sup>28</sup>. Further, Pearson’s product

moment correlation coefficients were used to determine whether any association was evident between shoulder counter-rotation and pelvic to shoulder separation angles, in addition to selected lower trunk kinematic variables. Correlation coefficients between 0.2 to 0.4 were considered weak, 0.4 to 0.7 as moderate and greater than 0.7 as strong<sup>29</sup>. All analyses were conducted using SPSS V11.0 for Windows (SPSS Inc., Chicago, Illinois). The level of statistical significance was set at  $p < 0.05$ .

## **5.4 Results**

The average back foot impact shoulder angle and associated average shoulder counter-rotation were  $234^{\circ}$  ( $s=18$ ) and  $41^{\circ}$  ( $s=16$ ) respectively, whilst the average back foot flat shoulder angle and associated shoulder counter-rotation were  $227^{\circ}$  ( $s=18$ ) and  $34^{\circ}$  ( $s=15$ ) respectively. Accordingly, the percentage of bowlers classified in each action type varied when using these two definitions. When back foot impact was utilised to determine shoulder alignment, 39 of the 50 bowlers (78%) were determined to have used a mixed action, while eight (16%) used a mid-way action and three (6%) used a side-on action. When the back foot flat definition was utilised, 30 bowlers (60%) were classified as mixed, 12 (24%) as mid-way and 8 (16%) side-on. No bowler was deemed to have used a front-on bowling action when either definition was used.

The proportion of lower trunk extension, contralateral side-flexion and ipsilateral axial rotation used by bowlers of each action type when classified using both definitions is displayed in Table 5.3. There was no significant difference in the percentage of lower trunk extension, contralateral side-flexion and ipsilateral axial rotation used by the mixed action bowlers compared with the non-mixed action bowlers (Table 5.3) although medium effect sizes were found for contralateral lower trunk side-flexion ( $d=0.62$ ) and ipsilateral rotation ( $d=0.57$ ) when the back foot impact definition was utilised. Also, there was no difference ( $t = 0.117$ ,  $p=0.91$ ) in the minimum shoulder angle obtained by the mixed (mean  $194^{\circ}$ ,  $s=9$ ) and non-mixed action (mean  $193^{\circ}$ ,  $s=11$ ) bowlers.

Strong correlations ( $r = 0.85 - 0.86$ ,  $p=0.00$ ) were found between the shoulder angle at both back foot impact and back foot flat and the magnitude of shoulder counter-rotation. Further, there was a significant, weak correlation found between shoulder counter-rotation, determined using the back foot impact definition, and ipsilateral lower trunk rotation ( $r = 0.34$ ,  $p=0.02$ ). There was no correlation between shoulder counter-rotation and the proportion of lower trunk extension or side-flexion using either the back foot impact or back foot flat definition (Table 5.4).

The minimum shoulder angle typically occurred just prior to front foot impact whilst the maximum pelvic to shoulder separation occurred, on average, 0.03 seconds after front foot impact (Figure 5.4a). Maximum lower trunk extension took place, on average, 0.01 seconds after front foot impact whilst maximum ipsilateral rotation and contralateral side-flexion occurred slightly later in the delivery stride at an average of 0.04 and 0.05 seconds after front foot impact respectively (Figure 5.4b).

Table 5.3 Lower trunk movement, expressed as a percentage of range of motion for extension, ipsilateral rotation and contralateral side-flexion, utilised by bowlers of each action type, and grouped averages for non-mixed and all bowlers. Data are presented for two back foot contact shoulder alignment instants; back foot impact and back foot flat. All mean (s) data are percentages of the maximum lower trunk range of motion attained during the standing range of motion trial.

Action Type	Back Foot Impact						Back Foot Flat					
	Extension		Contralateral Side-Flexion		Ipsilateral Rotation		Extension		Contralateral Side-Flexion		Ipsilateral Rotation	
Mixed	27	(21)	132	(27)	81	(19)	29	(22)	131	(27)	80	(19)
Midway	14	(17)	118	(27)	76	(23)	24	(16)	124	(22)	83	(22)
Side-on	38	(16)	108	(34)	52	(13)	14	(21)	126	(39)	76	(22)
All Non-mixed	20	(19)	115	(28)	69	(23)	20	(18)	125	(29)	76	(22)
All bowlers	26	(21)	129	(28)	79	(20)	26	(21)	129	(28)	79	(20)
Mixed v Non Mixed ( <i>t</i> value)	0.98		1.85		1.79		1.58		0.82		0.67	
Mixed v Non Mixed ( <i>P</i> value)	0.33		0.07		0.08		0.12		0.42		0.50	
Effect Size ( <i>d</i> value)	0.35		0.62		0.57		0.47		0.22		0.19	



Table 5.4 Correlations,  $r$  ( $P$  value), between shoulder counter-rotation, measured using two different definitions of back foot contact 1) back foot impact (BFI) and 2) back foot flat (BFF), and shoulder angle at back foot impact/flat, the minimum shoulder angle and the percentage of range of motion (%ROM) of the lower trunk kinematic variables of interest. Significant correlations in indicated in bold.

	%ROM Extension	%ROM Contralateral Side Flexion	%ROM Ipsilateral Rotation	Minimum Shoulder Angle	Shoulder Angle at BFI <sup>1</sup> / BFF <sup>2</sup>
Shoulder Counter- Rotation - BFI	-0.04 (0.21)	0.2 (0.16)	0.34 (0.02)	-0.04 (0.78)	0.86 (0.00) <sup>1</sup>
Shoulder Counter- Rotation - BFF	0.08 (0.60)	0.21 (0.14)	0.26 (0.07)	0.05 (0.74)	0.85 (0.00) <sup>2</sup>

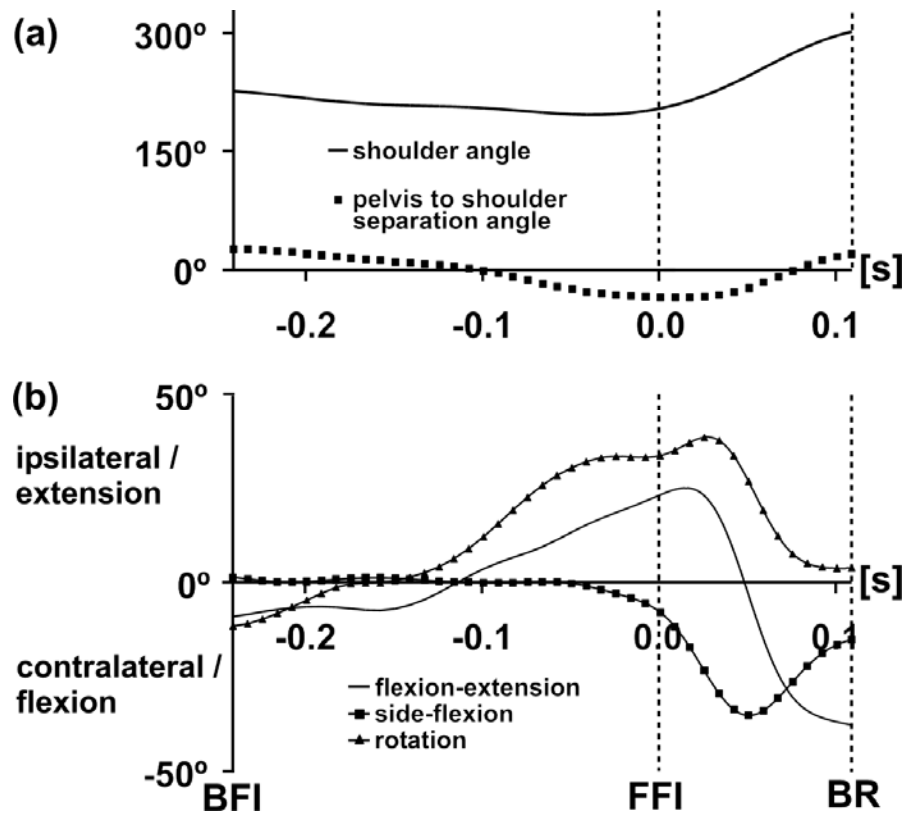


Figure 5.4a) Typical shoulder angles and pelvic to shoulder separation angles, and b) lower trunk flexion-extension, side-flexion and rotation angles during the delivery stride of fast bowling. Delivery stride events are back foot impact (BFI), front foot impact (FFI) and ball release (BR).

## 5.5 Discussion

Originally, fast bowling classification systems were designed to broadly describe bowling technique and biomechanical factors affecting performance<sup>7,30</sup>. However, these systems have evolved in an attempt to identify fast bowlers at risk of low back injury<sup>8,11,13</sup>. Despite initiatives aimed at enabling coaches to recognize potentially ‘unsafe’ action types, the prevalence of low back injuries, particularly contralateral side lumbar stress injuries, remains high<sup>1,2</sup>. In addition, the mechanism by which supposedly dangerous action types result in excessive stress on the contralateral side lumbar posterior elements is unclear.

An aim of this experimental study was to investigate the relationship between variables used in the fast bowling action classification system commonly employed in the United Kingdom<sup>14</sup> and Australia<sup>13</sup> and potentially injurious kinematics of the lower trunk during fast bowling. As reported in other studies that have used a similar classification system<sup>12,13,31</sup>, a high proportion of the professional fast bowlers were deemed to use what is currently considered to be an unsafe action type i.e. the mixed action.

There has been criticism of a lack of reporting and standardisation of the back foot contact phase instants at which shoulder angles have been measured in previous studies of fast bowling technique<sup>13</sup>. The effect of using different back foot contact shoulder angle instants (back foot impact and back foot flat) on the calculation of shoulder counter-rotation and action classification was quantified in this study (Table 5.2). Measuring shoulder alignment at back foot impact resulted in a higher average shoulder counter-rotation than when the later, back foot flat definition was employed (41° versus 34°). Average shoulder counter-rotation measurements reported in previous studies have ranged from 25° to 35°<sup>9,10,12,13,17</sup> which may suggest that a shoulder alignment definition somewhere after back foot impact was utilised. Alternatively, if previous studies did actually measure shoulder alignment at back foot impact, it may be that this cohort actually displayed greater levels of shoulder counter-rotation.

Using the back foot flat definition when measuring shoulder alignment resulted in a greater proportion of fast bowlers being classified as non-mixed i.e. side-on and midway. However, no significant difference in the percentage range of motion of the lower trunk kinematic variables of interest existed between mixed and non-mixed action bowlers in either definition. Burnett and colleagues<sup>16</sup> in the only other study of 3D kinematics of the lower trunk in fast bowling, also found no significant difference in lower trunk kinematics of mixed and non-mixed action bowlers. However, when they examined effect sizes (differences of  $d > 0.7$  in particular), a non-significant trend towards mixed action bowlers having a greater magnitude of contralateral lower trunk side-flexion was identified<sup>16</sup>. In the current study, when using the back foot impact shoulder alignment definition, medium effect sizes were found for the relationship between action type (mixed versus non-mixed) and lower trunk contralateral side-flexion and ipsilateral rotation (Table 5.3). Only a small effect size was found for extension. Furthermore, only small effect sizes were found for all lower trunk kinematic variables when using the back foot flat definition. Therefore, although the contralateral lateral bending and ipsilateral rotation results were close to statistical significance, when examining these results with consideration of the findings of the Burnett *et al.*<sup>16</sup> study, we 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.

All bowlers in this study adopted a relatively side-on alignment of the shoulders just prior to front foot impact (Figure 5.1c) regardless of shoulder alignment (front-on, midway or side-on) at back foot impact or back foot flat (Figure 5.1a and 5.1b). The implication of this is that all bowlers who had a front-on shoulder alignment at back foot impact or back foot flat had shoulder counter-rotation greater than 30° and were therefore classified as 'mixed'. Other investigators have remarked on a similar inability of bowlers who are front-on at back foot impact to maintain this orientation throughout the delivery stride<sup>12, 13</sup>. Therefore, it seems that

attaining a relatively side-on alignment of the shoulders just prior to front foot impact is a typical feature of the fast bowling action.

Pars interarticularis stress is reported 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<sup>20</sup>. The current action classification variables; back foot contact shoulder angle, back foot contact pelvic to shoulder separation and shoulder counter-rotation, are measured between back foot impact and front foot impact. During this phase the lower trunk is typically positioned in a relatively neutral posture when compared with just prior to front foot impact and through to ball release (Figures 5.1 & 5.3b). Therefore, as the lower trunk is in a relatively neutral position and the front (contralateral) foot is not in contact with the ground, there is likely to be relatively little stress on the contralateral side lumbar partes interarticulares.

Temporal analysis revealed that the lower trunk movements which are known to produce high contralateral facet joint contact forces i.e. lower trunk extension, contralateral side-flexion and ipsilateral rotation<sup>20</sup>, typically peaked just after front foot impact (Figure 5.4b). This lower trunk posture also occurred at the time that front foot ground reaction (compression) forces are known to be high<sup>7, 8, 13, 19</sup>. The combination of these two factors i.e. large facet joint contact forces and compression, produces high stress in the contralateral posterior bony elements of the lumbar spine<sup>20, 32</sup>. When repeated in high volume, as would be the case with professional fast bowlers, it could be speculated that this mechanism may provide the aetiology for the high rate of contralateral side lumbar bony stress lesions observed in elite fast bowlers<sup>3, 5, 6</sup>.

Hyperextension of the lumbar spine is thought to be the primary mechanism of injury in other sports with a high rate of lumbar stress fractures such as gymnastics<sup>33</sup> and American Football<sup>34</sup>. Previous authors have suggested that excessive shoulder counter-rotation may force the lumbar spine into hyperextension<sup>3, 35, 36</sup>. However, there was no correlation found between

shoulder counter-rotation and the proportion of lower trunk extension utilised by fast bowlers in this study, who on average, utilised only a relatively small proportion of their available lower trunk extension range of motion (26%). This places in question the importance of this movement in the aetiology of lumbar stress injuries within the population of senior elite fast bowlers.

Descriptively speaking, the greatest proportion of lower trunk range of motion utilised by the fast bowlers in this study was in contralateral side-flexion. During the front foot contact phase of the delivery stride fast bowlers utilised approximately 1.3 times the amount of side-flexion they obtained during the standing range of motion trial. This was probably due to the inertia of upper body and trunk causing significantly greater “elastic zone” motion of the spine whilst bowling as opposed to slow active side-flexion in standing. However, such a large amount of contralateral lower trunk side-flexion was not expected as maximum side-flexion occurred during a phase of the bowling action where the lower trunk was also extended and rotated to the ipsilateral side. These coupled movements should have reduced the range of available side-flexion<sup>21</sup>. Therefore, it might be concluded that, in accordance with the mechanical modelling studies of Chosa and colleagues<sup>20</sup> and de Visser and colleagues<sup>32</sup> this position of extreme contralateral lower trunk side-flexion, in combination with large ground reaction forces, is potentially the most significant stressor of the contralateral side lumbar partes interarticulares. However, in saying this, prospective studies are required to investigate the possible causal links between postures such as excessive lower trunk side-flexion and lumbar bony stress injury.

Shoulder counter-rotation during the delivery stride of fast bowling has previously been proposed to be an indicator of spinal torsional stress<sup>8,9,37</sup> and in this study a significant correlation, albeit weak, was found between shoulder counter-rotation and the proportion of ipsilateral lower trunk rotation when using the back foot impact definition only. However, using shoulder counter-rotation to directly estimate the degree of torsional stress in the lumbar spine may be problematic. This is due to the fact that shoulder counter-rotation is a significantly

removed derivative of whole trunk rotation<sup>38</sup> which occurs during the back foot impact to front foot impact phase of the bowling action. Alternatively, maximal lower trunk rotation occurs much later, during the front foot contact phase, and is in the opposite direction to the trunk rotation that occurs during the initial portion of back foot contact (Figure 5.4). Furthermore, a mechanical modelling study has indicated that rotational stresses alone are unlikely to be the major pathomechanical factor in lumbar stress injury<sup>20</sup>. Additionally, in comparison to contralateral side-flexion, the proportion of ipsilateral lower trunk rotation utilised by fast bowlers was relatively low (79% of rotation versus 129% of side-flexion). This may suggest a greater contribution of side-flexion, compared with rotation or extension, in the production of contralateral side lumbar bony stress. However, mechanical modelling studies using 3D lower trunk kinematic data such as that reported in this study, in addition to accurate spinal muscle geometric data<sup>32</sup>, are required to more precisely model the location and magnitude of lumbar bone stress associated with fast bowling.

The current study examined a professional adult fast bowling cohort as opposed to an adolescent fast bowling cohort. It is possible that professional fast bowlers have a different mechanism of back injury/re-injury and a slightly different technique to adolescents where a high magnitude of shoulder counter-rotation has been related to back injury<sup>3, 8, 9, 11</sup>. Professional fast bowlers have already bowled for years in training and in matches and they may have already survived the high-risk period through adolescence where they are known to be prone to back injury<sup>3, 8, 9, 11</sup>. Thus, professional fast bowlers may have a higher level of resilience than adolescents, or they may have a bowling technique that can withstand a higher volume of deliveries. Senior professional fast bowlers have previously been found to have a large prevalence of lumbar spine radiological abnormalities<sup>6</sup> and typically many would have missed some playing time due to back injury<sup>1, 2</sup>. It is possible that as part of back injury management, senior fast bowlers may have been advised to alter their bowling actions. Senior professional fast

bowlers may also have had more bowling technique coaching than adolescent fast bowlers in previous studies. However, in adult or adolescent fast bowling populations, we propose that coaches and biomechanists should pay greater attention to spinal positioning during the front foot impact phase of the delivery stride, especially the magnitude of contralateral side-flexion.

## **5.6 Conclusion**

A very high percentage of fast bowlers in this, and other studies, have been classified as having a mixed bowling action whilst no bowlers in this study were classified as front-on. This was the case regardless of whether the back foot impact or back foot flat method was used to define the back foot contact shoulder angle. Further, fast bowling action characteristics currently used to identify potentially dangerous action types may not be directly related to the likely pathomechanics of contralateral side lumbar stress injuries. It is proposed that concurrent lower trunk extension, ipsilateral rotation in addition to 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, further prospective and mechanical modelling studies are required to determine the relationship between lower trunk kinematics, variables previously found to be related to back injury e.g. shoulder counter-rotation, and lumbar spine stress injuries in fast bowlers.



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## **CHAPTER 6 - Study V**

In this chapter a combination of factors that have been examined earlier in this thesis are examined. Very little is known about the contribution of factors such as lumbar MRI appearance, fast bowling action and lower trunk kinematics and paraspinal muscle morphology to the high rate of lower back injury (particularly acute stress injury) and the associated lost match and training time, amongst professional fast bowlers in cricket.

Therefore, the aim of this study was to examine the relationship between fast bowler lower back injury occurrence (within on season either side of the one in which testing was conducted) and the following factors measured at a time when the participants were asymptomatic and bowling competitively; selected bowling action and delivery stride trunk kinematic variables, the lumbar MRI appearance of the partes interarticulares and intervertebral discs, and paraspinal muscle asymmetry.

## **Relationships between acute lumbar stress injury, trunk kinematics, lumbar MRI and paraspinal muscle morphology in fast bowlers in cricket.**

### **6.1 Abstract**

This study examined the relationship between lower back injury occurrence and selected factors measured when the 48 professional fast bowling subjects were bowling competitively. Factors examined in this study included: bowling action type (mixed or non-mixed) and the degree of delivery stride shoulder counter-rotation, maximal and the maximal percentage (of standing) range of motion (ROM) in lower trunk extension, contralateral side-flexion and ipsilateral rotation, MRI appearance of the lumbar spine posterior bony elements and intervertebral discs, and the degree of functional cross-sectional area (FCSA) asymmetry of the lumbar paraspinal muscles. A motion analysis system was used to collect the kinematic data and MRI was used to obtain the lumbar bone, disc and FCSA data. Subjects were grouped from pre-existing medical records as having either i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury. Statistical analysis compared groups i) and ii) only. Twelve participants (25% of the cohort) suffered an acute lumbar stress injury (stress fracture or stress reaction) within one season either side of the testing date. Action classification variables were not found to be associated with acute lumbar stress injury occurrence. Bowlers with acute lumbar stress injury used a smaller percentage ROM of lower trunk side-flexion during the delivery stride and a non-significantly greater amount of lower trunk extension than the participants who did not suffer significant lower trunk injury. The MRI appearance of the non-dominant side lumbar posterior elements and absence of intervertebral disc degeneration was related to acute stress injury occurrence. A relationship between paraspinal muscle asymmetry and acute lumbar stress injury was not identified. Further investigation of the effect of coupled lower trunk motion on non-dominant side lumbar bone stress and the relationship between MRI

acute bone stress changes and acute lumbar stress injury is indicated. Regular lumbar spine MRI scanning of elite fast bowlers may help identify early acute stress changes before injury occurs.



## 6.2 Introduction

Fast bowlers in cricket are known to suffer a high prevalence of lower back injury <sup>1</sup>. The category of lower back injury that accounts for the greatest amount of missed playing time in this group of athletes is stress injury of the lumbar partes interarticulares <sup>1,2</sup> which typically requires rehabilitation periods of at least four months duration <sup>3</sup>.

Radiological investigations undertaken using computed tomography (CT) and magnetic resonance imaging (MRI), have shown a high prevalence of acute and chronic bony stress changes in the partes interarticulares of the lumbar spine in fast bowlers. These occur predominantly at the lower lumbar levels, on the opposite side to the bowling arm <sup>4-8</sup>. In addition, a high prevalence of premature intervertebral disc degeneration has also been reported in both elite junior <sup>9,10</sup> and senior professional fast bowlers <sup>4</sup>. However, the relationship between these radiological findings, pain, functional disability (impairment in day to day tasks), cricket specific disability e.g. missed games by bowlers, and potential risk factors for low back injury in fast bowlers remains unclear.

Bowling technique, workload and physical risk factors have previously been associated with lower back injuries in fast bowlers. With regard to technique factors, the adoption of a 'mixed' bowling action, characterised by large counter-rotation of the shoulders during the delivery stride, is a factor that has been repeatedly associated with lower back injury in fast bowlers <sup>7,9-11</sup>, although the precise pathomechanics linking the mixed action to lumbar stress injury are yet to be elucidated. However, the predominantly non-dominant (non-bowling arm) side lumbar partes interarticulares stress injuries are likely to be due to repeated end-range lumbar side-flexion combined with rotation and extension, which occurs when the front foot contacts the ground during the delivery stride of fast bowling <sup>12-15</sup>.

Bowling related workload has also been implicated in the development of lumbar injury amongst elite fast bowlers, and there is increasing evidence to support this theory <sup>11, 16, 17</sup>. Dennis *et al.* <sup>16</sup> in their study of elite senior Australian fast bowlers reported that bowlers who averaged less than two days between bowling sessions, or bowled more than an average of 188 deliveries per week in training and in matches were at a significantly increased risk of injury compared with bowlers who bowled fewer deliveries, or bowled less frequently.

With respect to individual physical factors, a strong relationship between quadratus lumborum volume asymmetry and increased incidence of L4 pars interarticularis stress injuries was previously reported in a group of elite junior fast bowlers <sup>18</sup>. Further, a study examining the functional cross-sectional area (defined as the CSA of lean muscle tissue within the paraspinal muscles' fascial boundaries) of the lumbar paraspinal muscles in elite senior fast bowlers with a high prevalence of partes interarticulares stress injuries, found concurrently a high prevalence of muscle asymmetry, consistent with hypertrophy of the dominant side quadratus lumborum muscle <sup>19</sup>. This study also reported that the dominant side multifidus (in both fast bowlers and active controls), and the non-dominant side psoas in the fast bowlers, had a tendency to be asymmetrically larger. It has been hypothesised that asymmetry of the quadratus lumborum muscle might place greater shear loading on the non-dominant side L4 pars interarticularis predisposing it to stress injury <sup>18</sup>. In contrast, a recent finite element modelling study indicated that this type of quadratus lumborum asymmetry may in fact assist in reducing lumbar stress <sup>14</sup>.

The aim of this study was to examine the relationship between fast bowler lower back injury occurrence (within on season either side of the one in which testing was conducted) and the following factors measured at a time when the participants were asymptomatic and bowling competitively; selected bowling action and delivery stride trunk kinematic variables, the lumbar MRI appearance of the partes interarticulares and intervertebral discs, and paraspinal muscle asymmetry. There were a series of hypotheses related to this study. These hypotheses were 1)

acute lumbar stress injured fast bowlers would show a larger shoulder counter-rotation during the delivery stride and would utilise a greater proportion of available lower trunk range of motion during fast bowling, 2) Fast bowlers who sustained an acute lumbar stress injury would have a higher prevalence of MRI acute bony stress changes and intervertebral disc degeneration, 3) acute lumbar stress injured fast bowlers would have greater incidence and magnitude of lumbar paraspinal muscle asymmetry.

## **6.3 Methods**

### *6.3.1 Subjects and experimental protocol*

This study recruited 48 professional male fast bowlers from English County Cricket clubs. This sample represented approximately 25% of the professional fast bowlers playing first class County Cricket. Subjects were considered as fast bowlers by the England and Wales Cricket Board (ECB) fast bowling coach. The mean ( $\pm$  standard deviation) age, height and mass of the subjects was  $22 \pm 3$  years,  $1.87 \pm 0.06$ m and  $84 \pm 7$  kg respectively. Ethical approval for this study was obtained from the Human Research Ethics Committees of the University of Nottingham, UK and Curtin University of Technology, Western Australia.

This study contained several sets of data. Subjects' lower back injury occurrence was collected from pre-existing ECB and County Club injury records. Lower trunk three-dimensional (3D) motion analysis and MRI scanning was performed on the same day in either 2003 (32 subjects) or 2005 (16 subjects), when subjects were deemed fit to bowl by their County Physiotherapist and all subjects had bowled three times per week, on average, in either practice sessions or matches during the current season. A Vicon Motion Analysis System (Oxford, UK) was used to obtain the required fast bowling trunk kinematic variables whilst MRI was used to

determine both; the prevalence of abnormalities in the lumbar intervertebral discs and partes interarticulares, and the morphology of the lumbar paraspinal muscles.

### 6.3.2 *Data collection*

#### 6.3.2.1 Lower back injury occurrence

Information regarding the subjects' incidence of lower back injury spanning the County cricket seasons before, during and after the one in which they underwent MRI scanning and 3D motion analysis was collected i.e. the 2002 to 2004 seasons for those subjects tested in 2003, and the 2004 to 2006 seasons for those tested in 2005. This data was obtained from two sources, they being; injury records held by their ECB or Club Physiotherapist and injury statistics collected as part of the ECB Injury Surveillance Scheme <sup>2</sup>. In this context, injury was defined as any lower back pain or dysfunction that prevented a player from being fully able to play or train in their normal cricketing role, regardless of whether they were required to attend training or play in a match on that day <sup>2</sup>. The data collected was limited to the lower back injury diagnosis (denoted by the Club Physiotherapist using the Orchard Code system) <sup>20</sup> and the number of cricket days missed (training and playing) due to the injury. Diagnoses were made based on clinical examination by either the Club Physiotherapist and/or Medical Consultants. Where acute lumbar stress injury (acute stress fracture or acute bony stress reaction) was diagnosed, clinical examination findings were corroborated by medical imaging modalities. Clinical characteristics were typically; bowling related LBP which was often localised to the base of the spine on the non-bowling arm side and reproduction of symptoms with lumbar extension, or, combined lumbar extension and side-flexion or rotation performed whilst standing on one leg i.e. the "Stork Test" <sup>21</sup>. Imaging studies typically consisted of a combination of either; Single Photon Emission CT (SPECT) followed by reverse gantry Computed Tomography (CT) or, MRI followed by reverse gantry CT. To ensure that only significant low back injuries were recorded, only injuries that resulted in a minimum of seven consecutive days missed cricket during the

above mentioned data collection period were used to classify subjects as having a significant occurrence of low back injury.

#### 6.3.2.2 Motion analysis protocol

A 12 camera Vicon Motion Analysis System (Oxford, UK) operating at 120 Hz was used to measure the degree of shoulder counter-rotation and the three-dimensional (3D) kinematics of the lower trunk during the delivery stride of fast bowling and during a standing range of motion (ROM) trial. A standard marker set placed on bony landmarks was used to define shoulder, lower thorax and pelvic reference frames. Six bowling trials were collected before selecting the best three (maximum velocity trials with minimal marker loss) of each bowler for further analysis along with the standing ROM trial. Full details of these procedures are outlined in Ranson *et al.*<sup>13</sup> (Chapter 5).

#### 6.3.2.3 MRI protocol

MRI scans were obtained using a GE Medical Systems 1.5 Tesla MRI scanner at a time when the subjects were bowling competitively without lower pain. The scanning protocol comprised T1 and T2-weighted sagittal and axial sequences, and sagittal STIR sequences which were used to grade the MRI appearance of the lumbar intervertebral discs and partes interarticulares. The sagittal sections covered out to the lateral border of the lower lumbar posterior elements and were of 3 mm thickness. Sequence parameters were TR 500, TE 13 ms for the T1 weighted images; TR 8000, TE 50, TI 130 ms for the STIR images. To allow cross-sectional imaging of the lumbar paraspinal muscles; quadratus lumborum and the lumbar multifidii, axial T2 weighted images were obtained at seven spinal levels; they being the lower vertebral end plate of L1 to L5 and the upper vertebral endplate of L5 and S1. Full details of these procedures are outlined in Ranson *et al.*<sup>22, 23</sup>.

### 6.3.3 *Data analysis*

#### 6.3.3.1 Lower back injury occurrence

Subjects were categorised into three groups according to their low back injury occurrence (defined in Section 6.2.2.1). This was performed as follows:

- i) no significant lower back injury (subjects had either missed no cricket or, had not missed more than six consecutive days of cricket due to lower back injury)
- ii) acute stress injury (acute stress fracture or stress reaction resulting in more than six days lost cricket)
- iii) other lumbar injury resulting in more than six days of lost cricket

The average number of cricket days lost due to lower back injuries by players in each group was calculated.

#### 6.3.3.2 Bowling action classification and 3D kinematics of the lower trunk during fast bowling

Shoulder counter-rotation was determined by subtracting the minimum (most side-on) shoulder angle from the shoulder angle at back foot impact (the first frame at which the back foot came into contact with ground during the delivery stride). Bowlers with greater than 30° shoulder-counter rotation were classified as having a mixed action and bowlers with less than 30° shoulder counter-rotation were classified as having a non-mixed action<sup>4, 24</sup>.

Full details pertaining to the reconstruction of the pelvic and lower trunk local reference frames are outlined elsewhere (Chapter 5)<sup>13</sup>. The maximum lower trunk extension, contralateral side flexion and ipsilateral rotation utilised during the delivery stride of fast bowling was calculated. These values were then expressed as a percentage of the maximum ROM attained in each of these three movements during the ROM trial. A mean of the three trials was taken for the purpose of further analysis. All action classification and trunk kinematic variables had high ICC

values (range 0.86 - 0.97) and low %SEM values were found for all variables (range 1.5 - 9.1%) apart from lower trunk extension which had moderate %SEM values (17.2%)<sup>13</sup>.

#### 6.3.3.3 Assessment of the lumbar partes interarticulares and intervertebral discs

MRI images were independently assessed and graded by two experienced musculoskeletal radiologists using pre-existing classification systems adapted from Hollenburg *et al.*<sup>25</sup> and Pfirrmann *et al.*<sup>26</sup> for the partes interarticulares and intervertebral discs respectively. Previous analysis has shown substantial reliability<sup>27</sup> of the intra-examiner classification (kappa=0.6, percentage of agreement = 90%) and moderate reliability of inter-examiner disc classification (0.5, 87% respectively)<sup>4</sup>.

Subjects were grouped according to their lumbar partes interarticulares and disc MRI appearance. The partes interarticulares categories were i) normal or \*chronic stress reaction ii) acute stress changes i.e. stress reaction (marrow oedema +/- acute periosteal changes +/- acute stress fracture), or, iii) chronic stress fracture. The intervertebral disc groupings were i) normal or ii) disc degeneration (mild, moderate or severe degeneration at one or more lumbar levels).

Only the MRI appearance of the non-dominant side lumbar partes interarticularis was used in this study as previous research has shown that stress related changes in fast bowlers predominantly occur in this side of the spine<sup>5, 8, 23</sup>.

*\*multiple level chronic stress changes (cortical sclerosis and thickening) in the non-dominant side partes interarticulares are very common in fast bowler and thought to be a normal bony adaptation to the asymmetrical stress produced by the fast bowling action<sup>4, 28</sup>.*

#### 6.3.3.4 Lumbar paraspinal muscle morphometry

The FCSA of the lumbar paraspinal muscles at the L1 to S1 spinal levels was determined using image analysis software (Image J V1.3 - National Institutes of Health, USA). Firstly, cross-sectional area (CSA) measurements at each spinal level were determined by outlining the fascial boundary of the psoas, quadratus lumborum, erector spinae (combined iliocostalis and longissimus) and the lumbar multifidii muscles using the measurement function of the image processing software. The FCSA of these muscles (measured in cm<sup>2</sup>) was then obtained by thresholding out any pixels within each muscle's fascial boundary that did not represent lean muscle. This approach has previously been shown to have excellent reliability with a mean Intraclass Correlation Coefficient (ICC) of 0.97 (range 0.90–0.99) and mean relative Standard Error of Measurement (%SEM) of 2.6% (range 0.7–4.8%)<sup>22</sup>. The degree of asymmetry (percentage difference in FCSA) between the dominant and non-dominant side of each of the lumbar paraspinal muscles (psoas, quadratus lumborum, erector spinae and multifidus) was calculated for each muscle, at each spinal level.

#### 6.3.4 Statistical analysis

Descriptive statistics were used to depict the relationships between the three lower back injury occurrence groups (no significant lower back injury, acute lumbar stress injury and other lower back injury) and variables pertaining to i) number of days of cricket missed due to injury, ii) fast bowling action type, iii) lower trunk kinematics iv) lumbar MRI appearance and v) paraspinal muscle asymmetry. However, due to the small number of participants classified as having an occurrence of 'other' lower back injury and as the hypotheses of the study relate particularly to acute lumbar stress injury, statistical analysis was used only to compare the first two injury occurrence groups i.e. no significant lower back injury versus acute lumbar stress injury.



Fisher's exact tests<sup>28</sup> were used to examine the associations between lower back injury occurrence (no significant lower back injury versus acute lumbar stress injury) and the categorical variables: bowling action type (non-mixed or mixed), non-dominant side lumbar partes interarticulares MRI appearance and lumbar intervertebral disc MRI appearance. Independent t-tests were used to compare the two groups (no significant lower back injury and acute lumbar stress injury) in terms of mean levels of the continuous variables: shoulder counter rotation, maximal and percentage ROM of lower trunk contralateral side-flexion and ipsilateral rotation. Non-parametric tests (Mann-Whitney U test) were used for lower trunk extension kinematic variables because these did not satisfy assumptions of normality. Independent t-tests were also used to compare the two groups with respect to the degree of asymmetry of the four lumbar paraspinal muscles. All statistical Analyses were conducted using SPSS V14.0.

## **6.4 Results**

### *6.4.1 Bowling action type (non-mixed or mixed) versus lower back injury occurrence.*

A total of 17/48 (35%) of the bowlers in this cohort were classified as having a significant lower back injury as they missed more than 6 consecutive days of cricket due to lower back injury within one season of the one in which they were tested. Of these 17 bowlers, 12 (25% of the cohort) were diagnosed as having suffered an acute lumbar stress injury (stress fracture or stress reaction) for which they missed an average of 106 days of cricket. The five fast bowlers who were classified as having 'other' causes of lower back injury missed an average of 29 days of cricket (Table 6.1). There was no significant difference ( $p=0.7$ ) evident for the fast bowling action type between those who suffered acute lumbar stress injury versus those who had no significant lower back injury (Table 6.1).

Table 6.1 The number (and percentage) of subjects of each action type (non-mixed and mixed) with i) no significant lower back injury occurrence, ii) occurrence of acute lumbar stress injury or iii) other lower back injury. The average number of days missed per injury is also shown. Statistical analysis was performed between action type and lower back injury occurrence for groups i) and ii) only.

Lower back injury occurrence	Action Type			Average No. Days Missed per Injury
	Non-mixed N=13 (27%)	Mixed N=35 (73%)	Total N=48 (100%)	
*No significant lower back injury (n=31) (0-6 days missed)	8 (61%)	23(66%)	31 (65%)	1
*Acute stress injury (n=12) (>6 days missed)	4 (31%)	8 (23%)	12 (25%)	106
Other lumbar injury (n=5) (>6 days missed)	1 (8%)	4 (11%)	5 (10%)	29

\* Fisher's exact test: p=0.7

Furthermore, there was no difference in the magnitude of SCR employed by fast bowlers who suffered acute stress injury versus those who had no significant lower back injury (p=0.8) (Table 6.2).

Table 6.2 The mean (SD) shoulder counter-rotation used by fast bowlers who displayed i) no significant lower back injury occurrence, ii) occurrence of acute lumbar stress injury or iii) other lower back injury. Statistical analysis was performed between groups i) and ii) only.

Lower Back Injury Occurrence	Shoulder Counter-Rotation	
	Mean (SD)	p-value (*t-test)
No significant lower back injury (n=31) (0-6 days missed)	*41 (18.8)	0.8
Acute stress injury (n=12) (>6 days missed)	*40 (13.2)	
Other lumbar injury (n=5) (>6 days missed)	41 (19.6)	

There were no differences in the amount of maximal delivery stride range of motion (ROM) of lower trunk extension ( $p=0.20$ ), contralateral side flexion ( $p=0.30$ ) and ipsilateral rotation ( $p=0.09$ ) utilised by bowlers with no significant lower back injury and those with acute stress injury (Table 6.3). The fast bowlers who had suffered an acute lumbar stress injury utilised a lesser proportion of their range of motion (ROM) in contralateral side flexion than non-lower back injured fast bowlers ( $p=0.03$ ) but there was no difference in the percentage ROM of lower trunk extension ( $p=0.4$ ) and ipsilateral rotation ( $p=0.3$ ) utilised by these two groups of bowlers (Table 6.4).

Table 6.3 Lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury, versus maximal lower trunk extension, contralateral side flexion and ipsilateral rotation range of motion (ROM) utilised during the delivery stride of fast bowling. Statistical analysis was performed between groups i) and ii) only.

Maximal Lower Trunk ROM	Lower Back Injury Occurrence	Median (IQR)	p-value (Mann-Whitney)
Extension	No significant lower back injury (n=31) (0-6 days missed)	6 (2-10)	0.2
	Acute stress injury (n=12) (>6 days missed)	9 (2-13)	
	Other lumbar injury (n=5) (>6 days missed)	3 (0-14)	
		Mean (SD)	p-value (t-test)
Contralateral Side-Flexion	No significant lower back injury (n=31) (0-6 days missed)	33 (4.9)	0.3
	Acute stress injury (n=12) (>6 days missed)	31 (5.3)	
	Other lumbar injury (n=5) (>6 days missed)	33 (11.2)	
Ipsilateral Rotation	No significant lower back injury (n=31) (0-6 days missed)	32 (7.6)	0.09
	Acute stress injury (n=12) (>6 days missed)	27 (9.1)	
	Other lumbar injury (n=5) (>6 days missed)	30 (6.1)	

Table 6.4 Lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury, versus the maximal percentage range of motion (%ROM) of lumbar extension, contralateral side flexion and ipsilateral rotation and utilised during the delivery stride of fast bowling. Statistical analysis was performed between groups i) and ii) only.

Maximal Lower Trunk %ROM	Lower Back Injury Occurrence	Median (IQR)	p-value (Mann-Whitney)
Extension	No significant lower back injury (n=31) (0-6 days missed)	20 (6-31)	0.4
	Acute stress fracture (n=12) (>6 days missed)	27 (1-49)	
	Other lumbar injury (n=5) (>6days missed)	10 (0-48)	
		Mean (SD)	p-value (t-test)
Contralateral Side-Flexion	No significant lower back injury (n=31) (0-6 days missed)	135 (26.2)	<b>0.03</b>
	Acute stress injury (n=12) (>6 days missed)	115 (22.5)	
	Other lumbar injury (n=5) (>6 days missed)	141 (43.3)	
Ipsilateral Rotation	No significant lower back injury (n=31) (0-6 days missed)	80 (24.5)	0.3
	Acute stress injury (n=12) (>6 days missed)	71 (24.8)	
	Other lumbar injury (n=5) (>6 days missed)	75 (17.4)	

Significant differences in bold.

6.4.2 *Relationship between lower back injury occurrence and the lumbar MRI appearance of the non-dominant side lumbar partes interarticulares and intervertebral discs*

The relationship between the subjects' lower back injury occurrence and the MRI appearance of their non-dominant side lumbar partes interarticulares is shown in Table 6.5. There was a difference evident in the non-dominant side lumbar partes interarticulares MRI appearance of the fast bowlers who had an occurrence of acute stress injury compared with those with no significant lower back injury ( $p=0.001$ ). Of note, seven (70%) of the 10 subjects who had acute stress changes on MRI when they were asymptomatic at the time of testing, suffered an acute lumbar stress injury within one season either side of the year of testing.

Table 6.5 Lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury, versus the MRI appearance of the non-dominant side lumbar partes interarticulares. Statistical analysis was performed between groups i) and ii) only.

Lower Back Injury Occurrence	MRI Appearance Non-Dominant Lumbar Partes Interarticulares			
	Normal or Chronic Stress Reaction	Acute Stress Changes	Chronic (Old) Fracture	Total
*No significant lower back injury (n=31) (0-6 days missed)	24 (75%)	3 (30%)	4 (67%)	31 (65%)
*Acute stress injury (n=12) (>6 days missed)	3 (9%)	7 (70%)	2 (33%)	12 (25%)
Other lumbar injury (n=5) (>6 days missed)	5 (16%)	0 (0%)	0 (0%)	5 (10%)
Total	32 (100%)	10 (100%)	6 (100%)	48 (100%)

\*Fisher's exact test:  $p=0.001$

There was also a difference ( $p=0.05$ ) in the lumbar intervertebral disc MRI appearance of the fast bowlers who had an occurrence of acute stress injury when compared with those with no significant lower back injury. Nine (75%) of the 12 subjects who had an occurrence of acute lumbar stress injury had a normal MRI appearance of all lumbar discs whilst 19 (61%) of the 31 subjects who had no occurrence of significant lower back injury had the MRI appearance of disc degeneration at one or more lumbar levels (Table 6.6).

Table 6.6 Lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury, versus the MRI appearance of the lumbar intervertebral discs. Statistical analysis was performed between groups i) and ii) only.

Lower Back Injury Occurrence	MRI Appearance of Lumbar Intervertebral Discs		
	Normal Disc	Disc Degeneration	Total
*No significant lower back injury (n=31) (0-6 days missed)	12 (52%)	19 (76%)	31 (65%)
*Acute stress injury (n=12) (>6 days missed)	9 (39%)	3 (12%)	12 (25%)
Other lumbar injury (n=5) (>6 days missed)	2 (9%)	3 (12%)	5 (10%)
Total	23 (100%)	25 (100%)	48 (100%)

\*Fisher's exact test:  $p=0.05$

#### 6.4.3 Relationship between lower back injury occurrence and paraspinal muscle asymmetry

The degree of lumbar paraspinal muscle (psoas, quadratus lumborum, erector spinae and multifidus) FCSA asymmetry at each spinal level, and for the sum of all spinal levels, according to participants lower back injury occurrence is shown between Tables 6.7 to 6.10 inclusive.

There was no difference in the degree of FCSA asymmetry of any of the paraspinal muscles, at any spinal level and when all levels were summed, between the fast bowlers who suffered acute stress injury and those who had no significant lower back injury (range of  $p$ -values = 0.2-0.9).



Table 6.7 Psoas FCSA asymmetry (percentage difference in dominant to non-dominant side FCSA) at each lumbar level, according to lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury. Statistical analysis was performed between groups i) and ii) only. Positive FCSA values indicate the dominant side FCSA was larger.

Lower Back Injury Occurrence	Mean (SD) % difference in dominant to non-dominant side Psoas FCSA					
	L2	L3	L4	L5 superior	L5 inferior	All Levels Summed
*No significant lower back injury (n=31) (0-6 days missed)	1.3 (-11.8)	2.2 (10.3)	-2.0 (8.5)	-4.3 (9.6)	-3.7 (10.8)	-1.5 (7.5)
*Acute stress injury (n=12) (>6 days missed)	0.3 (11.2)	0.3 (7.6)	-2.3 (8.4)	-5.5 (5.9)	-6.2 (11.1)	-2.9 (5.5)
Other lumbar injury (n=5) (>6 days missed)	-2.8 (20.1)	-5.0 (7.9)	-5.5 (6.8)	-2.9 (6.7)	-1.7 (13.2)	-3.6 (8.6)
*p-value (t-test)	p=0.8	p=0.6	p=0.9	p=0.7	p=0.5	p=0.6

Table 6.8 Quadratus Lumborum FCSA asymmetry (percentage difference in dominant to non-dominant side FCSA) at each lumbar level, according to lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury.

Statistical analysis was performed between groups i) and ii) only. Positive FCSA values indicate the dominant side FCSA was larger.

Lower Back Injury Occurrence	Mean (SD) % difference in dominant to non-dominant side Quadratus Lumborum FCSA				
	L1	L2	L3	L4	All Levels Summed
*No significant lower back injury (n=31) (0-6 days missed)	5.1 (-21)	1.3 (18.2)	7.1 (15.1)	7.1 (21.1)	6.2 (-12)
*Acute stress injury (n=12) (>6 days missed)	15.5 (-21.2)	6.4 (22.1)	5.0 (20.3)	8.6 (15.4)	9.9 (-13.4)
Other lumbar injury (n=5) (>6 days missed)	14.3 (-14)	1.5 (-8.3)	-0.7 (17.7)	10.4 (18.3)	6.1 (-7.8)
*p-value (t-test)	p=0.2	p=0.4	p=0.7	p=0.8	p=0.4

Table 6.9 Erector Spinae FCSA asymmetry (percentage difference in dominant to non-dominant side FCSA) at each lumbar level, according to lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury. Statistical analysis performed between groups i) and ii) only. Positive numbers indicate the dominant side FCSA was larger.

Lower Back Injury Occurrence	Mean (SD) % difference in dominant to non-dominant side Erector Spinae FCSA					
	L1	L2	L3	L4	L5 superior	All levels Summed
*No significant lower back injury (n=31) (0-6 days missed)	-0.7 (7.1)	2.9 (8.9)	2.1 (9.8)	-3.2 (10.7)	-3.0 (16.7)	-0.6 (6.7)
*Acute stress injury (n=12) (>6 days missed)	1.2 (6.2)	6.0 (12.1)	1.5 (15.6)	-0.5 (16.0)	3.3 (13.4)	2.8 (8.9)
Other lumbar injury (n=5) (>6 days missed)	-0.4 (11.5)	8.3 (8.3)	-5.3 (18.3)	1.3 (14.2)	3.1 (9.8)	1.7 (9.7)
*p-value (t-test)	p=0.4	p=0.4	p=0.4	p=0.5	p=0.2	p=0.2

Table 6.10 Multifidus FCSA asymmetry (percentage difference in dominant to non-dominant side FCSA) at each lumbar level, according to lower back injury occurrence i) no significant lower back injury, ii) acute lumbar stress injury or iii) other lower back injury. Statistical analysis performed between groups i) and ii) only. Positive numbers indicate the dominant side FCSA was larger.

Lower Back Injury Occurrence	Mean (SD) % difference in dominant to non-dominant side Multifidus FCSA							
	L1	L2	L3	L4	L5 superior	L5 inferior	S1	All levels summed
*No significant lower back injury (n=31)	3.6 (13.1)	3.5 (12.1)	5.3 (8.6)	1.1 (11.0)	-0.9 (20.2)	3.9 (9.1)	1.3 (12.4)	3.2 (-6.2)
*Acute stress injury (n=12) (>6 days missed)	3.6 (13.1)	-0.9 (15.0)	4.3 (19.7)	2.2 (10.0)	3.9 (7.6)	1.5 (11.0)	4.4 (6.9)	3.4 (-7.3)
Other lumbar injury (n=5) (>6 days missed)	3.6 (13.1)	-9.7 (24.6)	5.0 (16.2)	4.5 (10.8)	-4.9 (20.0)	13.7 (9.8)	11.8 (13.7)	5.5 (-10.9)
*p-value (t-test)	p=0.4	p=0.3	p=0.8	p=0.8	p=0.5	p=0.5	p=0.4	p=0.9

## 6.5 Discussion

The high incidence (25% of the participants) and prevalence of lower back stress injuries occurring within one season either side of the date of testing is further evidence that this particular injury type remains a significant problem in professional cricket <sup>1, 2, 6, 29</sup>. It is likely that the stresses that lead to lumbar injury in fast bowlers are produced by combination of several risk factors including; bowling technique <sup>7, 11, 24</sup>, ball velocity <sup>11</sup> and workload <sup>11, 16, 30</sup>. Other possible risk factors include lumbar muscle imbalances <sup>31</sup>, age, genetic factors, physical preparation, footwear and playing surfaces. As with other relatively homogenous groups of

athletes who are likely to be highly motivated to play in spite of pain and post-injury<sup>32</sup>, psychosocial factors may not be as important as they are with lower back pain in the general population<sup>33-35</sup>. Although the aetiology of acute lumbar stress injury in fast bowlers is probably to be due to a combination of risk factors, in other athletes the most significant predictor of the future lower back injury is a history of LBP<sup>32</sup> and this is likely to also be the case with fast bowlers. This study aimed to examine the relationship between lower back injury occurrence, particularly lumbar stress injury, and factors measured when the fast bowling subjects were bowling competitively. These factors were bowling action type, selected lumbar kinematic variables, MRI appearance of the lumbar spine partes interarticulares, intervertebral discs and the lumbar paraspinal muscle morphology.

The first part of the first hypothesis of this study was that acute lumbar stress injured fast bowlers would have larger delivery stride shoulder counter-rotation than those who had no significant lower back injury. In this study fast bowlers were classified as having a mixed action if they had shoulder counter-rotation of over 30°<sup>13,24</sup>. Portus *et al.*<sup>5</sup> found that shoulder counter-rotation values were found to be significantly higher in bowlers who had suffered lumbar stress fractures when compared with non trunk-injured bowlers. However, in this study there was no difference in the amount of shoulder counter-rotation utilised by bowlers who had suffered an acute lumbar stress injury and non lower back-injured fast bowlers. A limitation of both this and previous studies is that it is not possible to determine what the bowlers' action type was when they were injured as actions were classified at a time when the subjects were symptom free. It is possible that bowlers who suffered a lumbar stress fracture prior to the time of testing may have previously adopted a mixed action which was later remodelled to reduce shoulder counter-rotation as part of their rehabilitation. In addition, a high percentage of fast bowlers in both this and the Portus *et al.*<sup>5</sup> study had large shoulder counter-rotation that caused them to be classified

as having a mixed action (73% and 62% respectively). Therefore, it is difficult to argue a case for using action classification to identify those at risk of lumbar stress injury.

There are further limitations to the use of shoulder alignment measures e.g. shoulder counter-rotation, to infer relative risk of lower back injury in fast bowlers. Shoulder alignment is a significantly removed derivative of trunk rotation<sup>36</sup> and although it has been previously shown to correlate with upper trunk rotation during the back foot contact to front-foot contact phase of the delivery stride<sup>37</sup> it is probably not an accurate indicator of trunk rotation after the front foot contact instant. In addition, shoulder counter-rotation is measured during the back foot contact to front foot contact phase of the delivery stride, a period in which the spine is in a relatively neutral posture and the contralateral (non-dominant side) lower limb is not in contact with the ground<sup>13</sup>. Therefore, trunk kinematics at this stage of the delivery stride not likely to be directly related to the pathomechanics of non-dominant side acute lumbar stress fracture. Furthermore, trunk rotation variables alone are unlikely to be major contributors to, or indicators of, stress production in the posterior bony elements of the lumbar spine<sup>38</sup>.

The second part of the first hypothesis of this study was that fast bowlers who suffered acute lumbar stress injury would utilise a greater amount and proportion of lower trunk extension, contralateral side-flexion and ipsilateral rotation, lower trunk kinematic variables thought to induce stress in the contralateral (non-dominant) side posterior bony elements of the spine<sup>38</sup>. The only lower trunk kinematic variable that discriminated the acute lumbar stress injury group from the no lower back injury group was the maximal proportion of contralateral side-flexion which was invariably attained during the front foot contact to ball release phase of the delivery stride. Unexpectedly, this variable was found to be significantly less in the acute lumbar stress injured participants. A potential reason for this finding might be offered by examination of the lower trunk kinematic data which indicated that the degree of maximal extension and percentage ROM of extension was non-significantly larger in the acute lumbar

stress injury group when compared with the no significant lower back injury group (9° versus 6° and 27% versus 20% respectively).

Previous researchers have shown that lower trunk axial rotation is reduced when the spine is positioned in either flexed or extended postures<sup>39</sup>. When fast bowling, maximal lower trunk extension generally occurs just prior to maximal contralateral side-flexion, during the front foot contact to ball release phase of the delivery stride (Figure 5.4)<sup>13</sup>, and it could be speculated that the acute lumbar stress injured fast bowlers had less contralateral side-flexion due to some of the available ROM being utilised by a more extended lower trunk posture. Unfortunately, during this study we were unable to measure the maximal proportion of total available coupled ROM (combined extension, contralateral side-flexion and ipsilateral rotation) utilised during the delivery stride making it impossible to estimate the contribution of coupled lower trunk motion to non-dominant side partes interarticulares stress during fast bowling. However, as even the acute lumbar stress injured fast bowlers used an average of well over 100% of the available standing ROM of contralateral side-flexion (115%), it is likely this movement in combination with lumbar extension and ipsilateral rotation, is a significant mechanical contributor to bony stress production.

In this study fast bowling lower trunk kinematics were measured when the participants were at the start of a bowling spell. Burnett *et al.*<sup>40</sup> and Portus *et al.*<sup>41</sup> are the only investigators to have examined kinematic variables over the length of a long bowling spell, measuring respectively, shoulder alignment and counter-rotation in elite junior fast bowlers over 12 overs and, first grade fast bowlers over 8 overs. Both studies provided some evidence that bowlers who have a more front-on shoulder alignment at back foot contact have a tendency to shoulder counter-rotate further later in the bowling spell. Further studies are required to determine if the lower trunk kinematics of professional and elite junior fast bowlers are affected by fatigue.

The second hypothesis of this study was fast bowlers who sustained an acute lumbar stress injury would have a higher prevalence of MRI acute bony stress changes and intervertebral disc degeneration than those who had no significant lower back injury. A relationship between the MRI appearance of the non-dominant side lumbar partes interarticales and lumbar stress injury occurrence was identified in this study. The relationship between imaging findings and LBP is controversial in the related literature. Bennett *et al*<sup>42</sup> in an MRI study of elite level gymnasts with and without LBP reported that MRI findings of stress fracture (spondylolysis and spondylolsthesis) and lumbar stress reaction (pedicle or posterior element bone oedema) were isolated to gymnasts with current LBP. This study provided further evidence that acute MRI stress changes may be specific indicators of acute bony stress injury risk. Specifically, seven of the ten fast bowlers who had the MRI appearance of acute stress changes were diagnosed with a lumbar stress injury (acute fracture or reaction) within a season prior to (N=2) or after (N=5) the MRI testing. At the time of testing these bowlers were pain free. Therefore, regular (e.g. annual), lumbar spine MRI scanning may enable early identification of acute bony stress prior to symptoms occurring. This may be an important preventive measure that may lead to a decrease in the amount of lost training and playing time.

A difference in the MRI appearance of the lumbar intervertebral disc between the participants who suffered a lower back stress injury and those with no significant injury was also identified in this study. Descriptive data suggested somewhat surprisingly, that those with acute stress injury had more normal MRI disc appearance. The finding that a high proportion of subjects (75%) who suffered acute lumbar stress fracture had normal MRI appearance of all lumbar discs, conflicts with the theory that a loss of disc height associated with intervertebral disc degeneration may lead to increased stress being placed on the posterior bony elements of the lumbar spine<sup>43,44</sup>. Further, 62 % of subjects who had no evidence of significant lower back injury had the MRI evidence of disc degeneration at one or more lumbar levels. Fast bowlers in



cricket have been shown to have a high prevalence of severe multi-level lumbar disc degeneration<sup>4</sup> however there is not a conclusive link between MR disc abnormalities and LBP in athletes<sup>42, 45</sup> or the general population<sup>46-49</sup>. In this study the disc appearance at the time of injury was not known, however, there does not seem to be a strong link between intervertebral disc imaging abnormalities and lower back injury occurrence in fast bowlers. In fact, it appears that either the bone or the intervertebral disc fails, but not both, and acute bone stress injury seems to lead to greater immediate disability, as evidenced by the large amount of cricket missed by players in this group. Further investigation of the compliance of the posterior bony elements versus intervertebral disc compliance in participants of differing levels of trunk mobility may aid identification of those at greater risk of acute bone stress injury.

The final hypotheses of the study was that acute lumbar stress injured fast bowlers would have a greater degree of asymmetry of the lumbar paraspinal muscles. In particular, greater asymmetry that matched a pattern of asymmetrical hypertrophy of the quadratus lumborum<sup>31</sup> was expected in the acute lumbar stress injured participants. Although asymmetry of the paraspinal muscles quadratus lumborum and multifidus is common in this population of fast bowlers<sup>19</sup> the degree of asymmetry was not statistically associated with acute lumbar stress injury occurrence in this cohort. Unequal side to side development of the paraspinal muscles, quadratus lumborum in particular, is likely to be at least partly due to the asymmetrical nature of the bowling action and in elite junior fast bowlers has been linked to the incidence of non-dominant side lumbar stress injury<sup>31</sup>. de Visser *et al.*<sup>14</sup> suggested that hypertrophy of the dominant side quadratus lumborum may be a compensatory mechanism, caused by the muscle eccentrically contracting in a forceful manner to control contralateral side-flexion during the delivery stride thereby unloading the non-dominant side lumbar spine. It may be that this mechanism has functioned to protect elite fast bowlers who have survived to reach professional

status and therefore quadratus lumborum asymmetry may be a relatively normal, rather than aetiological, finding in professional fast bowlers.

The relatively small world population of professional fast bowlers makes it extremely difficult to conduct studies with sufficient power to identify individual risk factors (or combinations of factors) involved in the aetiology of injuries such as acute stress fractures. Although, to date, this is the largest study of potential biomechanical risk factors for acute lumbar stress injury in professional fast bowlers, greater numbers of subjects need to be investigated prospectively in order to verify the significance of the trends identified. Factors not examined in this study, such as ball velocity, workload, growth rate (in juniors) trunk control and mobility, also require integrated investigation.

## **6.6 Conclusion**

The results of this study indicate that a high percentage of senior fast bowlers continue to sustain lower back injuries, predominantly acute lumbar stress injuries. Action classification and lower trunk kinematic variables obtained when bowlers were asymptomatic were not conclusively linked to acute lumbar stress injury occurrence. However, further investigation of the effect of coupled lower trunk motion on non-dominant side lumbar bone stress is indicated. The presence of acute MRI stress changes in the non-dominant side posterior elements seem to have a relationship with acute stress injury occurrence, pain and disability and regular lumbar MRI scanning may help identify early acute stress changes before injury occurs. Finally, although fast bowlers have a high prevalence of quadratus lumborum and lumbar multifidus being asymmetrically larger on the dominant side, there does not seem to be an obvious relationship between acute lumbar stress injury and these findings in professional fast bowlers.

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## CHAPTER 7 - Discussion and Conclusions

### 7.1 Introduction

Previous research <sup>1,2</sup> and the data in this doctoral investigation support that lower back injury, in particular acute lumbar stress injury (stress fracture and stress reaction) remains the major cause of lost playing time in professional fast bowlers in cricket. The aetiology of acute lumbar stress injury in fast bowlers is likely to be multifactorial (as outlined in Figure 1.3) with previous research citing relationships with fast bowling technique mainly focussing upon action type and the degree of shoulder-counter rotation <sup>3-5</sup>. More recently, acute lumbar stress injuries in elite junior fast bowlers have been linked to asymmetrical development of the paraspinal musculature, particularly quadratus lumborum <sup>6</sup>. However, the nature of this relationship is not clear and has not been examined in professional fast bowlers. There is also some evidence that factors such as workload, bowling speed and front knee angle during the bowling action <sup>4</sup> may also be related to injury risk. However, our overall knowledge of the causes of this unique injury problem is still limited. To date, strategies such as workload directives for fast bowlers and coach education pertaining to potentially injurious bowling action characteristics have not had a marked effect on reducing the acute lumbar stress injury rate in either elite junior <sup>7</sup> or professional fast bowlers <sup>2</sup>.

The majority of aetiological evidence is based upon studies of cohorts of elite, predominantly junior, Australian fast bowlers <sup>3,4,7,8</sup>. However, to date, there is a lack of research that has been conducted on professional fast bowlers regarding:

- the radiological appearance of fast bowlers lumbar spines, particularly the posterior bony elements i.e. the pedicles and partes interarticulares.
- paraspinal muscle morphology

- the kinematics of lower trunk during the delivery stride and their relationship to the likely pathomechanics of acute lumbar stress injury

It is these gaps in the related research that have stimulated the area of investigation for this doctoral thesis.

## **7.2 Summary and Conclusions**

The overarching aim of this thesis was to investigate the relationships between the unique pattern of acute lumbar stress injury suffered by fast bowlers in cricket and; their lumbar MRI appearance, characteristics of their lumbar paraspinal muscle morphology and previously unidentified lower trunk delivery stride kinematics. This thesis consisted of five distinct studies investigating the above, and the aims and findings of these studies are outlined below.

### ***Study 1 - Magnetic Resonance Imaging findings of the lumbar spine in asymptomatic professional fast bowlers in cricket***

The general aims of the first study of the thesis were to classify the MRI appearance of the lumbar intervertebral discs and posterior bony elements (partes interarticulares and pedicles) of non back-injured (at the time of testing) professional fast bowlers in cricket, in addition to a group of active controls. An further aim was to investigate the reliability of the classification systems adapted from Hollenburg *et al.*<sup>9</sup> (Table 2.1) and Pfirrmann *et al.*<sup>10</sup> (Table 2.2) for the lumbar posterior elements and discs respectively.

The study identified that professional fast bowlers have a high prevalence of multi-level, non-dominant side chronic stress reactions and acute stress changes (bone marrow oedema and periostitis) in the posterior bony elements of the lumbar spine. Furthermore, disc degeneration was present in a high number of bowlers and was more commonly seen at multiple lumbar levels

than when compared with active controls. However, disc degeneration is not a necessary precursor to acute bony lumbar stress changes. Fast bowlers can continue to bowl with chronic lumbar stress fractures; however, fast bowling with bilateral stress fractures may precipitate severe degeneration in the adjacent disc as evidenced by the severe disc degeneration that was observed in all fast bowlers who had chronic bilateral L5 stress fractures. The lumbar posterior bony element and intervertebral disc classification systems utilised in this study were shown to have acceptable intra and inter-observer reliability and it was found that these classification systems could be useful tools for the staging and re-assessment of disc and posterior element pathology in athletes in future studies. This paper provided further evidence<sup>11-13</sup> that acute bony stress changes can be reliably identified using MRI as a replacement for SPECT as a first line investigation into the clinical detection of suspected acute lumbar stress injuries. As well as the advantage of not involving exposure to ionising radiation, MRI also allows other structures possibly associated with lower back injury such as intervertebral discs, the facet joints, lumbar muscles and ligaments to be imaged. However, although acute lumbar stress fracture lines can often be identified on MRI, reverse gantry-CT may also be required as a second stage investigation to accurately delineate the bony architecture and the stage of any lumbar stress fractures<sup>13, 14</sup>.

***Study 2 - An investigation into the use of MRI to determine the functional cross sectional area of lumbar paraspinal muscles***

The measurement of the morphology of the lumbar paraspinal muscles has become the focus of several recent investigations into the aetiology of low back pain in the general population. Imaging modalities such as CT<sup>15</sup>, MRI<sup>16</sup> and ultrasound have been used to quantify paraspinal muscle CSA however, few investigators have sought to measure the functional CSA (FCSA, the area of muscle isolated from fat). In addition to the fact that MRI does not involve

exposure to ionising radiation, it has the additional advantage of allowing better tissue type discrimination and localisation than ultrasound. However, the reliability and validity of determining the FCSA of the lumbar paraspinal muscles using MR imaging has yet to be reported. Therefore, the aim of the second study of this thesis was to investigate the use of MRI and image processing software to determine the functional CSA of the lumbar paraspinal muscles.

To this end, T2 axial MR scans at the L1-S1 spinal levels of six participants were obtained using identical MR systems and scanning parameters. Lean paraspinal muscle, vertebral body bone and intermuscular fat was manually segmented using image analysis software to assign a grey scale range to the MR signal intensity emitted by each tissue type. The resultant grey scale range for muscle was used to determine FCSA measurements for each of the paraspinal muscles, psoas, quadratus lumborum, erector spinae and lumbar multifidus on each scan slice. As various biological, instrument and measurement factors can affect MR signal intensity<sup>17-22</sup>, a sensitivity analysis was conducted to determine the error associated in calculating FCSA for paraspinal muscle using a discrete grey scale range. It was concluded within the limitations of this study that the method to determine both muscle CSA and FCSA was both valid and highly reliable. It was found that even if the upper limit of the grey scale range for the MR signal intensity of muscle was under-estimated or over-estimated, the effect on the muscle FCSA measurements was small. Further, the error in using a discrete grey scale range for MR signal intensity of lean paraspinal muscle was quantified. This method presented in this paper has several applications namely; evidence based LBP rehabilitation<sup>15</sup>, biomechanical modelling of the musculoskeletal system<sup>23, 24</sup> and determination of segmental inertial parameters<sup>25-27</sup>.

### ***Study 3 - The lumbar paraspinal muscle morphometry of fast bowlers in cricket***

Paraspinal muscle asymmetries are thought to be a quantitative manifestation of lumbar paraspinal muscle dysfunction and a recent study associated the incidence of the most prevalent fast bowling low back injury diagnosis, non-dominant side lumbar stress fracture, with asymmetry of the quadratus lumborum muscle in a group of elite junior fast bowlers<sup>6</sup>. The authors suggested that asymmetry of the quadratus lumborum muscle placed a greater load on the non-dominant side L4 pars interarticularis predisposing it to stress injury. In contrast, a previous finite element modelling study<sup>23</sup> indicated that quadratus lumborum asymmetry might actually assist in reducing lumbar stress.

No study to date has investigated the morphology and symmetry of the lumbar paraspinal muscles in professional fast bowlers in cricket. Such *in-vivo* paraspinal muscle morphology data, specific to the population under investigation, is required for more accurate modelling of lumbar stress production in this unique group of athletes. Therefore, the general aim of the third study of this thesis was to examine and describe the FCSA of the lumbar paraspinal muscles in fast bowlers in cricket as compared with an active control group using the technique evaluated in the previous study.

In this study it was demonstrated that paraspinal muscle asymmetry was most prevalent in the quadratus lumborum of fast bowlers and was consistent with hypertrophy of the dominant side muscle. The dominant side multifidus in both the fast bowlers and controls and the non-dominant side psoas in the fast bowlers also had a tendency to be asymmetrically larger. The association between the pattern of paraspinal muscle asymmetry identified in this study and the aetiology of lower back injuries in fast bowlers in cricket requires further investigation. The data presented in this study may facilitate future efforts by informing prospective studies examining low back injury risk factors and by allowing the development of more accurate models of stress production in the lumbar spine during fast bowling. It may be that asymmetrical development of

the paraspinal muscles is a mechanism that has functioned to protect elite fast bowlers who have “survived” to reach professional status. For example, quadratus lumborum asymmetry in professional fast bowlers, may be a relatively normal finding, rather than a risk for risk factor for low back injury.

***Study 4 - The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket***

The aims of the fourth study of the thesis were to quantify the proportion of lower trunk motion utilised during the delivery stride of fast bowling and to investigate the relationship between the most accepted fast bowling action classification system <sup>5, 28</sup> and potentially injurious kinematics of the lower trunk. Three-dimensional kinematic data were collected from 50 male professional fast bowlers during three fast bowling trials and these were normalised to each bowler’s standing lower trunk range of motion. A high percentage of the fast bowlers used a mixed bowling action attributable to having shoulder counter-rotation greater than 30°. The greatest proportion of lower trunk extension (26%), contralateral side-flexion (129%) and ipsilateral rotation (79%) was utilised during the front foot contact phase of the fast bowling delivery stride. There was no significant difference in the proportion of available lower trunk extension, contralateral side-flexion and ipsilateral rotation range of motion used during fast bowling by mixed and non-mixed action bowlers.

A key finding of this study was, similar to several other studies <sup>5, 29, 30</sup>, a very high percentage of fast bowlers appeared to adopt a mixed bowling action whilst no bowlers in this study were classified as being front-on. Further, fast bowling action characteristics currently used to identify potentially dangerous action types may not be directly related to the likely pathomechanics of contralateral side lumbar stress injuries. It is proposed that coupled lower trunk extension, ipsilateral rotation in addition to 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.

***Study 5 - Relationships between acute lumbar stress injury, trunk kinematics, lumbar MRI and paraspinal muscle morphology in fast bowlers in cricket***

In the final study a combination of the factors described in earlier chapters in this thesis i.e. the lumbar MRI appearance of the partes interarticulares and intervertebral discs, paraspinal muscle asymmetry and selected bowling action and delivery stride trunk kinematic variables, were examined. Very little is known about the contribution of factors such as lumbar spine pathology as determined by MRI, paraspinal muscle morphology and fast bowling action and lower trunk kinematics to the high rate of lower back injury (particularly acute stress injury), and the associated lost match and training time amongst professional fast bowlers in cricket. Therefore, the aim of this study was to examine the relationship between fast bowler lower back injury occurrence (within one season either side of the season in which testing was conducted in) and the aforementioned factors measured at a time when the participants were asymptomatic and bowling competitively.

The results of this study indicated that a high percentage of professional fast bowlers in the United Kingdom continue to sustain lower back injuries, and these injuries are predominantly represented by acute lumbar stress injuries. Fast bowling action classification and lower trunk kinematic variables obtained when bowlers were asymptomatic were not conclusively linked to acute lumbar stress injury occurrence. However, further investigation of the effect of coupled lower trunk motion on non-dominant side lumbar bone stress is indicated.

The presence of acute MRI stress changes (particularly acute stress changes such as bone marrow oedema, periostitis and acute fracture lines) in the non-dominant side lumbar posterior elements seem to have a relationship with acute stress injury occurrence, pain and

disability. Regular lumbar MRI scanning may assist in identifying early acute stress changes before injury occurs. Intervertebral disc degeneration was less prevalent amongst professional fast bowlers who suffered acute stress injuries than those who had no significant lower back injury. This finding is somewhat contrary to previous assertions that disc degeneration precipitates acute bone stress<sup>31, 32</sup>, and this indicates that there may be differing mechanisms for MRI identified bony stress changes and intervertebral disc abnormalities. These differences are possibly attributable to factors such as bone health<sup>33</sup>, genetic predisposition to bone stress injury<sup>34</sup> and individual differences in robustness of the connective tissue.

Finally, although fast bowlers have a high prevalence of quadratus lumborum and lumbar multifidus being asymmetrically larger on the dominant side, there does not seem to be an obvious relationship between acute lumbar stress injury and these findings in professional fast bowlers.

### **7.3 Practical Implications of the Research**

The aim of multi-disciplinary sports injury research, as was conducted in this thesis, is to develop an evidence base that informs practice. There are several practical implications stemming from the research undertaken in this thesis that supports the aim of reducing the incidence and impact of lower back injury in fast bowlers.

As with other relatively homogenous groups of athletes who are likely to be highly motivated to play both through and post-injury<sup>35</sup>, psycho-social factors may not be as important as they are with lower back pain in the general population<sup>36-38</sup>. Amongst the general population with lower back pain the relationships between radiological imaging findings and pain and disability are controversial<sup>39-41</sup>, however, the homogenous nature of the athletes and the preponderance of a particular lumbar injury type i.e. non-dominant side acute stress injury, allows MRI to be used more effectively to predict and diagnose<sup>42</sup> lower back injury in this



group. A recommendation stemming from the first and fifth studies in this thesis is that MRI scans, reported by a radiologist experienced in identifying acute bony stress changes <sup>13</sup>, is an ideal first line investigation for suspected acute lumbar stress lesions. MRI could also be utilised as a screening tool with, for example, annual MRI scanning of elite junior and senior fast bowlers, to attempt to identify early acute stress changes i.e. bone marrow oedema and periostitis, before they progress to complete stress fracture, an injury that inevitably results in long periods of missed cricket <sup>43</sup>.

The method of measuring the FCSA of the lumbar paraspinal muscles developed in the second study, and employed in the third study of the thesis, has potential application in both the sporting and the general population. The technique developed in Chapter 3 of this thesis may allow mechanical models of acute lumbar bony stress during simulated athletic activity to incorporate accurate, *in-vivo* muscle size and shape data (as presented in Chapter 4), rather than relying on measurements of cadaveric paraspinal muscle morphology <sup>23, 24</sup>. Such a technique could also be used to gauge the extent of any LBP-related paraspinal muscle atrophy <sup>44, 45</sup> and the efficacy of subsequent rehabilitation programmes. Similarly, as quadratus lumborum asymmetry has been associated with acute lumbar stress fracture development in elite junior fast bowlers <sup>6</sup>, the method described could be used as an additional injury risk screening tool by allowing relatively quick and simple calculation of quadratus lumborum FCSA and subsequent muscle volume estimation.

The 3D motion analysis approach used in the fourth study of this thesis (Chapter 5) could form the basis for the development of ‘coach friendly’ biomechanical lower back injury risk analysis <sup>46</sup> that focuses on the likely pathomechanics of non-dominant side acute lumbar stress injury in fast bowlers i.e. extreme lower trunk extension, contralateral side-flexion and ipsilateral rotation during the front foot contact to ball release phase of the delivery stride. As mentioned in Chapter 5, elite junior fast bowlers may have different lower trunk kinematic

profiles to professional fast bowlers. Further investigation of the 3D lower trunk motion of junior fast bowlers is a recommended component of future prospective studies of the mechanical aetiology of acute lumbar stress injury in that group.

#### **7.4 Limitations of the Doctoral Investigation**

The relatively small world population of professional fast bowlers makes it extremely difficult to conduct studies with sufficient power to identify individual risk factors (or combinations of factors) involved in the aetiology of acute lumbar bony stress injuries. Although this is currently the largest study of potential biomechanical risk factors for acute lumbar stress injury in professional fast bowlers, greater numbers of subjects need to be investigated prospectively in order to verify the significance of the patterns identified.

The kinematic and MRI variables measured in this study were collected at a time when the fast bowlers were fit to bowl (although it should be acknowledged some players occasionally bowl with back pain) and it is possible that these variables may have altered between the time of testing and time of injury. For example, bowling action characteristics may have changed, consciously (due to coaching interventions, performance or injury reasons) or have adapted unconsciously, and it is known that muscle morphometry can change relatively quickly in response to both activity<sup>15</sup> and injury<sup>45</sup>.

Furthermore, although there may be a link between imaging of acute stress changes and the subsequent or previous occurrence of acute lumbar stress injury, the clinical relevance of lumbar spine MRI abnormalities in fast bowlers is not yet clear. Similarly, the MRI methods provide a static measure of muscle size and no consideration of muscle function was made in this thesis. *In-vivo* measurement of muscle function using biomechanical measurement techniques such as electromyography may on the surface be problematic due to the highly dynamic nature of fast bowling and the inaccessibility of some of the deep muscles of interest

e.g. quadratus lumborum and psoas. It is now possible to use MRI obtained pre and post exercise to provide insight into muscle activation and recruitment patterns<sup>47</sup> and this type of technology may be beneficial in future investigations of trunk muscle activity during fast bowling.

The wireless 3D trunk kinematic analysis approach utilised during this research is a progression from the pioneering 2D motion analysis studies<sup>3, 4, 8, 48-51</sup> and the only other published fast bowling 3D lower trunk motion analysis study<sup>52</sup>. However, current technology still only provides an indication of gross regional trunk kinematics and more sophisticated methods and models are required in order to more accurately estimate stress localised to the most vulnerable spinal region i.e. the lower levels of the non-dominant side of the lumbar spine.

## **7.5 Future Research Directions**

There are many directions that fast bowling research may take and below are just a few considerations for future research.

Many studies to date in the related literature have been cross-sectional in nature so for research in the field to progress, prospective studies examining a multitude of risk factors such as those outlined in this thesis are needed. For example, longitudinal designs conducted over several years that include cohorts of both junior and senior fast bowlers are required so that studies investigating lower back injury can be undertaken with sufficient statistical power. International collaboration may be required to provide adequate numbers of participants in trials aimed at investigating the combined effects of several potential lower back injury risk variables. However, these types of studies may then also need to consider that fast bowlers from other countries, cultures and races e.g. Afro-Caribbean or Asian, may have difference injury resistance and risk profiles.

Ideally such studies would integrate variables such as bowling workload, growth and physical preparation, lumbo-pelvic control and mobility, lower limb kinematics, footwear and playing and training conditions and surfaces. The influence of factors such as bone health <sup>33</sup>, bone density <sup>53</sup> and genetic predisposition <sup>34</sup> to bony stress injury may also need to be considered.

With respect to advancing cricket-specific knowledge using imaging modalities, research utilising dynamic imaging modalities such as functional MRI, may be required to establish the relationship between pain, function and vertebral bony and disc findings.

Mechanical modelling studies such as a multiple muscle version of the quadratus lumborum model developed by de Visser and colleagues <sup>23</sup> are needed to more accurately examine the potential protective <sup>23</sup> or injurious effects <sup>6</sup> of asymmetrical paraspinal muscle development. Such studies may include segmental coupled motion indices along with accurate muscle function and geometry in order to more closely determine the relationship between lower trunk kinematics, variables previously found to be related to back injury e.g. shoulder counter-rotation, and non-dominant side lower lumbar spine stress injuries in fast bowlers. Within this process, lower trunk motion needs to be evaluated when bowlers are fatigued, preferably in match situations. Technological innovations such as miniaturised motion sensors linked with telemetry systems may enable that to occur.

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## **APPENDICES**

### **Appendix 1    Healthy Volunteer's Information Sheet**

#### **Low Back Muscle Asymmetry and Low Back Injury in Fast Bowlers in Cricket**

**Name of Investigators:** Craig Ranson, Dr Mark Batt, Dr Rob Kerslake, Dr Angus Burnett

You have been invited to take part in a research study. Before you decide whether to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends and relatives if you wish to. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part or not. If you decide to take part you may keep this leaflet. Thank you for reading this.

#### **Background**

Research into the cause of low back injuries in fast bowlers in cricket has been carried out since the late 1980s. Several significant risk factors have been identified for injuries such as lumbar disc degeneration and stress fractures of the low back. Of these risk factors, the use of a mixed bowling action almost certainly makes a bowler more susceptible to injuring his or her lower back. Over bowling is also thought to be a major contributor to the epidemic of low back injuries that continue to occur in fast bowlers. Despite programs such as coach education as to the dangers of a mixed bowling action and fast bowling directives designed to minimise the effect of over bowling in young bowlers, low back injuries remain the most significant injury problem in the modern game. Stress fractures of the low back continue to account for the most

missed playing time due for professional fast bowlers in both English and Australian first class cricket.

Recently, a study has suggested that another factor, low back muscle asymmetry (a difference in muscle size on one side of the spine compared with the other), is associated with the development of low back stress fractures in elite young fast bowlers. The reason why muscle asymmetry occurs in the low back of fast bowlers has not been established. How this phenomenon might be related to, or even cause, low back injury in professional fast bowlers is also not known.

The purpose of this research project is to investigate if muscle asymmetry of the low back muscles is common amongst professional fast bowlers in County Cricket. The relationship between asymmetry of the low back muscles and other risk factors such as a mixed bowling action and previous back injury will also be investigated. This research is important because if muscle asymmetry of the low back is, as previous research has suggested, associated with an increased risk of low back injury in fast bowlers then why this is the case needs to be determined. Coaching and rehabilitation programs aimed at addressing muscle asymmetry of the low back can then be developed with a view to reducing the contribution of this factor to low back injuries in fast bowlers.

This study will be completed by March 2004.

#### **What does the study involve?**

Each subject in the study will have information collected regarding his previous history of low back injury. If subjects agree to take part in the study this information will be collected from subjects' personal injury records held by their club physiotherapist and from injury statistics collected as part of the ECB Injury Surveillance Scheme.

Each subject will undergo an MRI scan of their low back, which will be used to identify any asymmetry of certain muscles in that region. The MRI scan will also be used to classify the extent of any bone or disc damage in the subjects' lower backs. The scan will take approximately 20 minutes and will require you to remain quite still inside the scanning machine for the duration of the scan. There are no known adverse side effects of this type of scan however some people may find the enclosed space inside the scanner claustrophobic. Trained staff will be on hand to advise and assist should this occur. Scanning will take place at the East Midlands Nuffield Hospital in Derby, on **Monday September 15, 2003**.

Each subject will also be required to attend one other testing session which will allow data pertaining to your bowling action type, and movements of your lower back during bowling, to be collected. A computer motion analysis system will be used to capture and analyse each subject's bowling technique. This part to the study will be conducted at the indoor cricket school at Derbyshire County Cricket Club on the same day as the MRI scan i.e. Monday September 15, 2003. At least 20 minutes will be allowed prior to testing for subjects to complete their normal pre-bowling warm-up routine. Subjects will be required to bowl with a bare torso, as several small markers will be placed on the shoulders, chest and low back. Following marker placement subjects will be asked to bowl no more than 3 overs with their normal run-up and action. The computer system's cameras will be able pick up the location of these markers in space during the bowling action. This information will be fed to a computer, which will be used to analyse each subject's action. Total time for marker placement and bowling during testing should not exceed 20 minutes per subject tested.

### **Why have you been chosen?**

Thirty professional seam bowlers will be studied during this project. You have been invited to be a subject in this study as you meet the criteria we have set down for participants. These criteria include that all subjects must be seam bowlers who are members of the playing

squad of a first class County Cricket Club. All bowlers must be fit to bowl at the time of the study. Also, they will have played at least two seasons of county cricket and will have bowled at least 200 overs, in all competitions, during each of the previous 2 seasons. Subjects will not have any contraindications to MRI scanning.

**Do you have to take part?**

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

**What do I have to do?**

You will be requested not to take part in any heavy exercise in the 24 hours prior to each of the two testing sessions.

You will also be required to complete a standard medical screening form prior to having an MRI scan of your lower back.

**What are the possible disadvantages and risks of taking part?**

It is possible that the MRI scan may discover structural abnormalities in your lower back that you were previously unaware of. If this does occur and the abnormalities are considered to have the potential to cause you future pain or injury then you will be fully informed of any implications in this eventuality. Your General Practitioner will also be informed in writing and sent a copy of the MRI report. At no stage will any information regarding the result of your MRI scan be disclosed to any person, other than to yourself and your General Practitioner.

The motion analysis testing of your bowling action will not carry any greater injury risk than a typical indoor bowling practice session.

**What if something goes wrong?**

If you have any questions regarding this study please feel free to call. If you have any complaints in the way this research is being conducted please contact Craig Ranson, the lead investigator on 01332 388 108. If no satisfactory outcome is achieved then you should contact Mrs Louise Sabir, Ethics Committee Secretary, The Dean's Office, B Floor, The Medical School, Queen's Medical Centre, Nottingham, NG7 2UH.

**Will my taking part in this study be kept confidential?**

All information that is collected about you during the course of the research will be kept on a password-protected database and is strictly confidential. Any information about you that leaves the research unit will have your name and address removed so that you cannot be recognised from it.

Each research volunteer's own GP will be notified of his participation in the study.

**What will happen to the results of the research study?**

The results of the research will be published in an appropriate, peer reviewed scientific journal. Results will also be present to the Sports Medicine Advisory Group of the ECB. It is planned that the results will be published during 2004. Subjects will not be able to be identified in any report/publication.

**Who is organising and funding the research?**

The Professional Cricketer's Association and the Motion Analysis Research and Rehabilitation Centre will be funding the costs of the research.

**Who has reviewed the study?**

The study has been reviewed and approved by the Higher Degrees Committee of Edith Cowan University (Perth, Australia).



This study has also been reviewed and approved by the University of Nottingham Medical School Ethics Committee and by the Edith Cowan University Ethics Committee.

**Contact for Further Information**

If you have any questions regarding this study please feel free to call Craig Ranson on 01332 388 108 or 07796 938 552. If you have any complaints in the way this research is being conducted please contact Hugh Morris, ECB Performance Director on 020 7289 5619.

You will be given a copy of this information sheet and a signed consent form to keep.

The investigators would like to thank you for agreeing to participate in this study

## **Appendix 2     Healthy Volunteer's Consent Form**

### **Title of Project:**

Low Back Muscle Asymmetry and Low Back Injury in Fast Bowlers in Cricket

### **Name of Investigators:**

Craig Ranson, Dr Mark Batt, Dr Rob Kerslake, Dr Angus Burnett

Please read this form and sign it once the above named or their designated representative, has explained fully the aims and procedures of the study to you

- I voluntarily agree to take part in this study.
- I confirm that I have been given a full explanation by the above named and that I have read and understand the information sheet given to me which is attached.
- I have been given the opportunity to ask questions and discuss the study with one of the above investigators or their deputies on all aspects of the study and have understood the advice and information given as a result.
- I agree to the above investigators contacting my general practitioner to make known any relevant abnormalities that may be discovered on the low back MRI scan.
- I agree to comply with the reasonable instructions of the supervising investigator and will notify him immediately of any unexpected unusual symptoms or deterioration of health.
- I authorise the investigators to disclose the results of my participation in the study but not my name.
- I understand that information about me recorded during the study will be kept in a secure database. If data is transferred to others it will be made anonymous. Data will be kept for 7 years after the results of this study have been published.
- I authorise the investigators to disclose to me any abnormal test results.
- I understand that I can ask for further instructions or explanations at any time.

- I understand that I am free to withdraw from the study at any time, without having to give a reason for withdrawing.
- I confirm that I have disclosed relevant medical information before the study.
- I have not been a subject in any other research study in the last three months, which involved: taking a drug; being paid a disturbance allowance; having an invasive procedure (eg venepuncture >50ml, endoscopy) or exposure to ionising radiation.
- I confirm that I have not been exposed to more than 5 mSv of ionising radiation in the last 12 months.

**Name:** .....

**Address:** .....

**Telephone number:** .....

**Signature:** ..... **Date:** .....

**General Practitioner:** .....

**GP address:** .....

.....

I confirm that I have fully explained the purpose of the study and what is involved:

.....

I have given the above named a copy of this form together with the information sheet:

**Investigators Signature:** ..... **Name:** .....

**Study Volunteer Number:** .....

### Appendix 3 Curtin University of Technology Ethics Approval



#### memorandum

<b>To</b>	Craig Ranson, c/- Dr Angus Burnett, Physiotherapy
<b>From</b>	Linda Teasdale, Secretary, Human Research Ethics Committee
<b>Subject</b>	MONITORING OF RESEARCH PROJECT - Progress Report and Application for Renewed Approval - HR 74/2005
<b>Date</b>	12 April 2006

Office of Research and Development

**Human Research Ethics Committee**

TELEPHONE 9266 2784  
FACSIMILE 9266 3793  
EMAIL hrec@curtin.edu.au

Our records indicate that the Human Research Ethics Committee has granted approval for the following project:

**Approval No:** HR 74/2005

**Investigator:** Craig Ranson, Physiotherapy

**Supervisor:** Dr Angus Burnett

**Project Title:** "MRI, Lumbar muscle morphology, fast bowling technique and low back injury in cricket"

**Expiry Date:** 09/06/2006

In order to comply with the National Health and Medical Research Council *National Statement on Ethical Conduct in Research Involving Humans* it is necessary for the researcher to complete the attached FORM B and return to the address at the foot of this page.

Please ensure that the following directions are adhered to and the FORM B is returned as soon as possible.

1. Please indicate whether the project has been completed/abandoned/not commenced/not funded/or still in progress.
2. Please ensure that all questions are answered as appropriate and that signatures are placed where indicated.
3. ALL RESEARCHERS must return this form regardless of the stage of the project.

Your co-operation in this matter is very much appreciated.

A handwritten signature in black ink, appearing to read "Linda Teasdale".

Linda Teasdale  
Secretary, Human Research Ethics Committee

## Appendix 4 University of Nottingham Ethics Approval

Please quote protocol ref no C/9/2002

Direct line/e-mail  
+44 (0) 115 970 9905380  
Louise.Sabir@nottingham.ac.uk



09 October 2002

Mr Craig Ranson  
Derbyshire County Cricket Club  
County Ground  
Nottingham Road  
Derby  
DE21 6DA

**Faculty of Medicine  
and Health Sciences**

Medical School Ethics  
Committee  
Dean's Office  
B Floor  
The Medical School  
Queen's Medical Centre  
Nottingham  
NG7 2UH

Tel: +44 (0) 115 970 9.  
Fax: +44 (0) 115 970 9!

Dear Mr Ranson

**C/9/2002 – Ethics application for the research project entitled – The relationship between lumbar muscle asymmetry and low back injury fast bowlers in cricket.**

Thank you for your letter dated 30<sup>th</sup> September and enclosing the following:

- A proforma letter of invitation to potential subjects
- Revised Volunteer Consent Form
- Revised Volunteer Information sheet version

These have been reviewed and are satisfactory. Your response with regard to the power calculation for this study is also reasonable. This study is approved.

Approval is given on the understanding that the Conditions of Approval set out below are followed.

### **Conditions of Approval**

You must follow the protocol agreed and any changes to the protocol will require prior Ethic's Committee approval.

The Committee would expect to see a copy of the final questionnaire before it is used.

You promptly inform the Chairman of the Ethic's Committee of

- (i) deviations from or changes to the protocol which are made to eliminate immediate hazards to the research subjects.
- (ii) Any changes that increase the risk to subjects and/or affect significantly the conduct of the research
- (iii) All adverse drug reactions that are both serious and unexpected

**Please note that all correspondence and queries should be sent to my  
Ethics Committee Secretary Louise Sabir**

- (iv) New information that may affect adversely the safety of the subjects or the conduct of the study.

#### **ICH GCP Compliance**

The University of Nottingham Medical Research Ethics Committee is fully compliant with “the International Committee on Harmonisation/Good Clinical Practice (ICH/GCP) Guidelines for the Conduct of Trials involving the Participation of Human Subjects” as they relate to the responsibilities, composition, function, operations and records of an Independent Ethics Committee/Independent Review Board. To this end, it undertakes to adhere as far as is consistent with its Constitution, to the relevant clauses of the ICH Harmonised Tripartite Guideline for Good Clinical Practice adopted by the Commission of the European Union on 17 January 1997.

Yours sincerely



**Professor R C Spiller**  
**Chairman, Nottingham University Medical School Ethics Committee**

## Appendix 5 Edith Cowan University Ethics Approval

### **HUMAN RESEARCH ETHICS COMMITTEE**

For all queries, please contact:  
Research Ethics Officer  
Edith Cowan University  
100 Joondalup Drive  
JOONDALUP WA 6027  
Phone: 6304 2170  
Fax: 6304 2661  
E-mail: [research.ethics@ecu.edu.au](mailto:research.ethics@ecu.edu.au)



JOONDALUP CAMPUS

100 Joondalup Drive,  
Joondalup  
Western Australia 6027  
Telephone 134 328  
Facsimile (08) 9300 1257

ABN 54 361 485 361

8<sup>th</sup> July 2004

Mr Craig Alan Ranson  
Derbyshire County Cricket Club  
County Ground, Nottingham Road  
Derby UK DE21 6DA

Dear Mr Ranson

<b>PROJECT CODE</b>	02-121
<b>PROJECT TITLE</b>	The Relationship between Lumbar Muscle Asymmetry, Low Back Injury and Bowling Technique in Fast Bowlers in Cricket
<b>CHIEF INVESTIGATOR</b>	Mr C A Ranson

Thank you for your recent request for an extension on the above application and forwarding an Ethics Report Form.

I am happy to inform you that the changes to the research procedures and an extension for the above project to the 31<sup>st</sup> December 2005 have been approved and noted by the Human Research Ethics Committee.

Please continue to keep us informed of any changes to your research project.

Once again, with best wishes for success in your work.

Yours sincerely

A handwritten signature in black ink, appearing to read 'K Gifkins', with a stylized flourish to the left.

Kim Gifkins  
EXECUTIVE OFFICER  
Phone 6304 2170  
Fax: 6304 2661  
Email: [research.ethics@ecu.edu.au](mailto:research.ethics@ecu.edu.au)

Attachment – Conditions of Approval

cc: Dr Angus Burnett, Supervisor  
Mrs K Leckie, Manager Graduate School  
Ms R Treloar Cook, Administrative Officer, HDC

## Appendix 6 Lippincott Williams & Wilkins Copyright Permission



February 11, 2008

Craig Ranson  
ECB National Cricket Performance Centre  
Loughborough University  
LE11 3TU UK

**VIA EMAIL TO:** [Craig.ranson@ecb.co.uk](mailto:Craig.ranson@ecb.co.uk) November 30, 2007

**FEE:** None

**RE:** Ranson CA, Burnett AF, O'Sullivan PB, Batt ME and Kerslake, RW. The lumbar paraspinal muscle morphometry of fast bowlers in cricket. *Clinical Journal of Sport Medicine*. In press, 2007.

**USE:** Thesis

### CONDITION OF AGREEMENT

Permission is granted upon the return of this signed agreement to Lippincott Williams & Wilkins (LWW). Please sign and date this form and return to:

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David O'Brien, Worldwide Copyright Management  
351 W Camden Street, 4 North  
Baltimore, MD 21201  
USA



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Requestor accepts:



Date: 01.12.2007