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# Cricket fast bowling technique and lumbar bone stress injury

Peter Alway[1], Paul Felton[2], Katherine Brooke-Wavell[1], Nicholas Peirce[3], Mark King[1]

[1]School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK
[2]Department of Science and Technology, Nottingham Trent University, Nottingham, UK
[3]Department of Science and Medicine, England and Wales Cricket Board, Loughborough, UK

## ABSTRACT

**Introduction:** Lumbar bone stress injuries (LBSI) are the most prevalent injury in cricket. While fast bowling technique has been implicated in the aetiology of LBSI, no previous study has attempted to prospectively analyse fast bowling technique and its relationship to LBSI. The aim of this study was to explore technique differences between elite cricket fast bowlers with and without subsequent LBSI. **Methods:** Kinematic and kinetic technique parameters previously associated with LBSI were determined for 50 elite male fast bowlers. Group means were compared using independent samples t-tests to identify differences between bowlers with and without a prospective LBSI. Significant parameters were advanced as candidate variables for a binary logistic regression analysis. **Results:** Of the 50 bowlers, 39 sustained a prospective LBSI. Significant differences were found between injured and non-injured bowlers in: rear knee angle, rear hip angle, thoracolumbar side flexion angle and thoracolumbar rotation angle at back foot contact (BFC); the front hip angle, pelvic tilt orientation and lumbopelvic angle at front foot contact (FFC); the thoracolumbar side flexion angle at ball release and the maximum front hip angle and ipsilateral pelvic drop orientation. A binary logistic model, consisting of rear hip angle at BFC and lumbopelvic angle at FFC, correctly predicted 88% of fast bowlers according to injury history and significantly increased the odds of sustaining an LBSI (odds ratio: 0.88 and 1.25 respectively). **Conclusion:** Lumbopelvic motion is implicated in the aetiology of LBSI in fast bowling with inadequate lumbo-pelvi-femoral complex control a potential cause. This research will aid the identification of fast bowlers at risk of LBSI, as well as enhancing coaching and rehabilitation of fast bowlers from LBSI.

**Key Words:** Stress fracture, pace bowling, biomechanics, spondylolysis, lumbopelvic

## INTRODUCTION

Bone stress injuries are an overuse injury caused by the accumulation and propagation of linear microcracks across bone (Bennell et al., 1996). Bone stress injuries have been demonstrated to progress in severity from bone marrow oedema to stress fracture (Kountouris et al., 2018). Lumbar bone stress injuries (LBSI) are the most prevalent injury in cricket (Orchard et al., 2016) with a time loss which can exceed 8 months (Alway et al., 2019) and is likely have a deleterious effect on the development of fast bowlers. They are commonly observed in young (18-22 years old) fast bowlers at the L4 (35%) and L5 (33%) vertebra, and are almost exclusively unilateral (93%), presenting at the neural arch contralateral to the bowling arm (Alway et al., 2019). The neural arch, containing the pars interarticularis and pedicle, are the common sites of LBSI in fast bowlers due to their narrow structure and relative delayed maturation (Bogduk, 1997), which creates a weakened structure, resulting in comparatively increased bone strain in this area.

Incidence of LBSI is high in activities with repetitive flexion, extension and rotation of the lumbar spine such as gymnastics, baseball pitching and athletic throwing events (Tawfik et al., 2020) with LBSI commonly occurring bilaterally at L5 (Rossi and Dragoni, 2001; Soler and Calderón, 2000). This LBSI injury location differs to fast bowlers and a reason for the disparity may be due to the technique adopted in each activity which can directly affect the magnitude, direction and location of strain on bone (Bennell et al., 1999). A unique requirement of cricket bowling technique is that the elbow is not allowed to extend during the action (Marylebone Cricket Club (MCC), 2013). As a consequence fast bowlers often exhibit large amounts of contralateral trunk side flexion to globally orientate the arm optimally at ball release (Ranson et al., 2008). The timing of peak contralateral trunk side flexion typically coincides with high front foot vertical ground reaction forces, often in excess of 6 bodyweights ( Worthington et al., 2013), potentially generating large loads on the lumbar spine which could contribute to LBSI (Zhang et al., 2016).

Previous research has investigated the link between fast bowling technique and LBSI (Bayne et al., 2016; Elliott et al., 1992; Foster et al., 1989; Portus et al., 2004; Ranson et al., 2010). Initial studies attempted to link action classifications, defined using the orientation in the transverse plane of the pelvis and shoulders during the bowling action, with LSBI (Elliott et al., 1992; Foster et al., 1989; Portus et al., 2004). Although these classifications are far removed derivatives of lumbar spine kinematics (Senington et al., 2018), there has been some evidence linking the mixed classification (greater than 30° of shoulder counter-rotation or pelvis-shoulder separation at back foot contact) to LBSI (Portus et al., 2004). More recently a three-dimensional method has established a link between excessive contralateral thoracolumbar side flexion (Bayne et al., 2016; Ranson et al., 2008) during the front foot contact phase with LBSI and lower back injuries in fast bowlers.

Studies investigating technique as a cause of LBSI have been limited by small sample sizes due to the difficulties in obtaining LBSI cases. This has resulted in grouping all lower back injuries into one group, and retrospectively analysing bowling technique following LBSI. No study to date has prospectively analysed the link between fast bowling technique and LBSI. As a result, the aim of this study is to prospectively explore technique differences between elite cricket fast bowlers who sustain a LBSI and those who have never suffered LBSI.

## METHODS

### *Participants*

Elite male cricket fast bowlers, enrolled on an international performance pathway, provided written informed consent to participate in the study in accordance with the guidelines of the Loughborough University Ethics Advisory Committee. Fast bowlers were included in the prospective injury group if they sustained a LBSI within 2 years following their biomechanical assessment. Bowlers were included in the uninjured group if they had never sustained an LBSI; had a biomechanical assessment prior to the age of 22; and were at least 23 years old with a minimum of 150-match days of professional cricket at the end of the 2019 season (to ensure bowlers were outside the high-risk low career workload threshold, Orchard et al., 2015). All fast bowlers were required to undergo an MRI lumbar spine scan subsequent to their biomechanical assessment as a part of the ongoing England and Wales Cricket Board lumbar spine injury screening programme. A CT or CT SPECT scan was arranged to follow up those with diagnostic uncertainty.

### *Data Collection*

Each bowler performed a minimum of six maximum velocity deliveries on a ‘good length’ which was recorded using an 18 camera Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 300 Hz. Kinetic data were collected via a synchronised Kistler force plate (Type 9287B, Winterthur, Switzerland) operating at 1500 Hz. Data were collected in an indoor cricket facility incorporating a full-length artificial pitch with space for a full run-up. Any bowler whom an elite wicketkeeper would normally stand back to were defined as ‘fast,’ and all bowlers were deemed fit to bowl by a qualified physiotherapist. Forty-seven retro reflective 14 mm markers were attached to each fast bowler, positioned over bony landmarks in accordance with the marker set used by Worthington et al. (Worthington et al., 2013). In addition, a 2 $cm^2$ piece of reflective tape was added to the ball to determine the instant of release and velocity. Static and dynamic calibration trials were performed for each subject, allowing body segment length and neutral spine position to be calculated (Ranson et al., 2008). Ninety-five anthropometric measurements were taken enabling subject-specific segmental inertia parameters to be determined for each bowler (Yeadon, 1990).

### *Data Processing*

The bowling trial for each participant with the greatest ball velocity, minimal marker loss and where the front foot landed on the force plate was manually labelled and processed using Vicon Nexus software (OMG PLC, Oxford, UK). Trajectories of markers were filtered using a recursive fourth-order low-pass Butterworth filter with a cut-off frequency of 30 Hz (Winter, 1990). Back foot contact (BFC) was defined as the first frame in which the movement of the markers changed due to the contact of the foot with the ground, and front foot contact (FFC) was defined as the first frame in which vertical ground reaction force exceeded 25 N (Worthington et al., 2013). Ball release (BR) was determined from the frame in which the distance between the ball marker and the midpoint of a pair of markers over the wrist exceeded 20 mm relative to the previous frame (Worthington et al., 2013).

The joint centres for the ankle, knee, shoulder, elbow and wrist were calculated from the pair of markers placed medio-lateral across each joint (anterior-posterior for shoulder), such that their midpoint coincided with the joint centre (Worthington et al., 2013). The markers placed over the left and right anterior and posterior superior iliac spine were used to calculate the hip joint centres (Davis et al., 1991), while the mid-point of the posterior superior iliac spine markers defined the lumbopelvic junction (Worthington et al., 2013). Similarly, the thoracolumbar junction was defined as the mid-point of the markers placed on the xiphoid process and L1 spinous process (Worthington et al., 2013), and the cervicothoracic junction as the mid-point of the interclavicular notch and the C7 spinous process (Worthington et al., 2013).

The global coordinate system was defined with the y-axis pointed down the wicket, the x-axis towards the bowlers right, and the z-axis pointing vertically upwards. Local three-dimensional references frames were determined for 18 segments (head and neck; upper trunk; lower trunk; pelvis; 2 x upper arm; 2 x lower arm; 2 x hand; 2 x upper leg; 2 x lower leg; and 2 x two-segment feet) using three markers on each segment, where the z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the bowler's right and y-axis pointed forwards (Worthington et al., 2013). Global segment orientation and joint angles were calculated as Cardan angles, using an xyz sequence. For the global orientation the xyz rotations corresponded to tilt, drop and twist, respectively, with orientations described relative to the anatomical position and the bowling side (anatomical position = 180°; anterior tilt, contralateral drop and twist <180°). For the joint angles, the xyz rotations corresponded to flexion-extension, abduction-adduction, and longitudinal rotation, respectively (Worthington et al., 2013), with angles described relative to the anatomical position and the bowling side (anatomical position = 180°: flexion; and contralateral side flexion and rotation < 180°) except for the flexion-extension axis of the ankle (anatomical position = 90°; dorsi flexion < 90°) (Worthington et al., 2013). All angles reported within the results will correspond to the flexion-extension axis unless otherwise stated.

Previously investigated fast bowling action classification parameters were calculated using the shoulder and pelvis twist orientations (Portus et al., 2004). Shoulder counterrotation was calculated by subtracting the minimum shoulder twist orientation during the delivery stride from shoulder twist orientation at BFC (Portus et al., 2004). Pelvis-shoulder separation was calculated by subtracting the pelvis twist orientation from the shoulder twist orientation at BFC (Portus et al., 2004). Shoulder counterrotation was calculated by subtracting the minimum shoulder twist orientation during the delivery stride from the shoulder twist orientation at BFC (Portus et al., 2004). Similarly, the orientation of a lower thorax reference frame, defined by Ranson et al. (Ranson et al., 2008) using the three markers placed on the xiphoid process, and the T10 and L1 spinous processes, was determined relative to the pelvis as Cardan angles using an xyz sequence (anatomical position = $180^{o}$; flexion, and contralateral side flexion and rotation < 180°). The orientation of a front leg reference frame, defined using the hip and ankle joint centres (Worthington et al., 2013), and a front foot reference frame, defined using the MTP and ankle joint centres (Worthington et al., 2013), were determined relative to the global coordinate system as Cardan angles using an xyz sequence (anatomical position = 0°; anterior tilt, contralateral drop and twist < 0°). This allowed two kinematic parameters at FFC to be determined previously linked to peak ground reaction forces and time to peak force during the front foot contact phase of fast bowling. Front leg plant angle was defined as the tilt orientation of the front leg at FFC, and front foot plant angle as the tilt orientation of the front foot at FFC (Worthington et al., 2013). Front knee flexion was also determined between FFC and BR for similar reasons (Worthington et al., 2013).

Six kinetic parameters consisting of peak forces, average loading rates and impulse in the vertical and horizontal (braking) directions were determined (Worthington et al., 2013). Average loading rates were calculated as the peak force divided by the time from initial foot contact to the time of peak force (Hurrion et al., 2000). Peak forces, average loading rates and impulses were explored in absolute and normalised terms (using the bowlers' body mass), as it is unknown whether absolute or relative ground reaction force is a contributor to LBSI.

Ball release velocity was calculated over a period of 10 frames (0.033 s) from the instant of BR using the equations of constant acceleration. Run-up velocity (in the global y-direction) was calculated as the mean horizontal mass centre velocity over a period of 18 frames (0.060 s) immediately before the instant of BFC (Worthington et al., 2013). All radiological scans were read by board certified musculoskeletal radiologists with extensive experience in reporting lumbar spine scans in fast bowlers. LBSI's were defined as either stress reactions or stress fractures determined from radiological reports Stress reactions were defined as any report which identified evidence of bone marrow oedema (without fracture line), while acute stress fractures were defined by any report which identified evidence of incomplete, complete or multilevel stress fracture accompanied by bone marrow oedema which suggested the fracture site was active. Chronic inactive stress lesions were identified separately in separate analysis. These details were recorded in the England and Wales Cricket Board injury database at the time of the scan and extracted for current analysis.

### *Statistical Analysis*

All statistical analyses were performed within SPSS v.26 (IBM, USA). Normality of the data was determined by a Shapiro-Wilk test and equal variances were determined by Levene's test. To compare variables between injured and uninjured fast bowlers, independent samples t-tests were used with an alpha value of 0.05 (Sinclair et al., 2013). If the assumption of normality was violated for any variable, the non-parametric Mann-Whitney U test was performed instead. Similarly, if the assumption that the variance of homogeneity was violated for any of the variables, Welch's t-test was used. Effect sizes were calculated for all variables (Cohen, 1988).

To identify the key predictors of LBSI, the parameters which were significantly different between the injured and non-injured groups were put forward as "candidate" variables for input in a binary logistic regression model. To reduce the risk of Type 1 error only significant variables with medium or greater effect sizes were considered for entry into the binary regression model. Candidate variables were removed prior to entry if there was any evidence of multicollinearity (Pearson's correlation coefficient, $r > 0.7$, $p < 0.05$, Field, 2009). The entry requirement for the inclusion of a parameter into the regression equation was $p < 0.05$ with a removal coefficient of $p < 0.10$. To minimise the potential limitations of stepwise regression models, all possible binary logistic regression models were determined for comparison. The regression model was rejected if the odds ratio 95% confidence interval contained 1 (indicates the coefficient 95% confidence interval included zero).

## RESULTS

Fifty elite fast bowlers (age: 18.9 ± 1.9 years; mass: 83.0 ± 8.4 kg; height: 1.87 ± 0.06 m) who underwent biomechanical analysis met the criteria to be included within this study. Of these, 39 bowlers (age: 19.3 ± 2.0 years; mass: 83.2 ± 7.6 kg; height: 1.88 ± 0.06 m) sustained a prospective LBSI (injury age: 19.9 ± 2.1), while the other 11 bowlers (age: 19.8 ± 1.5 years; mass: 82.5 ± 11.3 kg; height: 1.86 ± 0.05 m) had no history of LBSI injury. A summary of the of the LBSI injuries experienced by fast bowlers can be found in Table 1. Both groups were comparable with similar age, height, and weight statistics ($p > 0.05$), however, at the end of the 2019 season, the fast bowlers with a prospective LBSI had played significantly fewer days of professional cricket to compared to their injury free counterparts (Median ± IQR: 104 ± 236 vs. 268 ± 264, ES > 0.5).

**Table 1: Severity and location of LBSI in elite cricket fast bowlers**

| | Stress Fracture N = 26 | | Stress Reaction N = 13 | | Total LBSI N = 39 | |
|---|---|---|---|---|---|---|
| **Vertebra** | **N** | **%** | **N** | **%** | **N** | **%** |
| L1 | 0 | 0 | 0 | 0 | 0 | 0 |
| L2 | 0 | 0 | 1 | 8 | 1 | 3 |
| L3 | 4 | 15 | 1 | 8 | 5 | 13 |
| L4 | 8 | 31 | 3 | 23 | 11 | 28 |
| L5 | 6 | 23 | 5 | 38 | 11 | 28 |
| Multilevel | 8 | 31 | 1 | 8 | 9 | 23 |
| Unknown | 0 | 0 | 2 | 15 | 2 | 5 |
| **Side (relative to bowling arm)** | | | | | | |
| Contralateral | 23 | 88 | 9 | 69 | 32 | 82 |
| Ipsilateral | 1 | 4 | 0 | 0 | 1 | 3 |
| Bilateral | 2 | 8 | 2 | 15 | 4 | 10 |
| Unknown | 0 | 0 | 2 | 15 | 2 | 5 |
| **Region** | | | | | | |
| Pars | 23 | 88 | 5 | 38 | 28 | 72 |
| Pedicle | 1 | 4 | 4 | 31 | 5 | 13 |
| Both | 2 | 8 | 0 | 0 | 2 | 5 |
| Unknown | 0 | 0 | 4 | 31 | 4 | 10 |

Five significant differences with a large effect size (d > 0.8, r > 0.5) and three significant differences with a medium effect size (d > 0.5, r > 0.3), were observed in the kinematic parameters calculated at key instants of the bowling action (Table 2). At the instance of BFC the injured bowlers had more flexed rear hip and knee angles, less contralateral thoracolumbar side flexion and more contralateral thoracolumbar rotation (Table 2). A further three parameters were significantly different at FFC with injured bowlers having more flexed front hip angles, more anterior pelvic tilt, and more extended lumbopelvic angles (Table 2). At ball release, the only significant difference was in the thoracolumbar side flexion angle with the injured bowlers less contralaterally side flexed than their non-injured counterparts (Table 2). Although not significant with an alpha value of 0.05 (p = 0.09), a medium effect size (d = 0.58) was found for the difference in the lumbopelvic side flexion angle, with injured bowlers more contralaterally side flexed at BR.

**Table 2: Group means and standard deviations for selected position and velocity parameters at the key instants of the fast bowling action for bowlers with and without a history of LBSI.**

| | **Back foot contact** | | **Front foot contact** | | **Ball release** | |
|---|---|---|---|---|---|---|
| **parameters** | **LBSI** | **non-LBSI** | **LBSI** | **non-LBSI** | **LBSI** | **non-LBSI** |
| ball release speed (m/s) | | | | | 35.1 ± 1.6 | 35.8 ± 1.9 |
| horizontal COM velocity (m/s) | 6.1 ± 0.5 | 6.1 ± 0.5 | | | | |
| shoulder orientation – twist (°) | 240 ± 16$^{*}$ | 236 ± 22 | 205 ± 27$^{*}$ | 199 ± 5 | | |
| pelvis-shoulder separation (°) | 21 ± 15 | 13 ± 24 | | | | |
| rear knee angle (°) | ***146 ± 11***$^{**}$ | ***156 ± 18*** | | | | |
| rear hip angle (°) | ***146 ± 10***$^{***}$ | ***156 ± 9*** | | | | |
| front foot plant angle (°) | | | -6 ± 19 | -9 ± 17 | | |
| front ankle angle (°) | | | 127 ± 21 | 129 ± 18 | | |
| front knee angle (°) | | | 163 ± 6 | 163 ± 6 | 164 ± 23 | 169 ± 23 |
| front hip angle (°) | | | ***130 ± 9***$^{***}$ | ***137 ± 7*** | 118 ± 11$^{**}$ | 124 ± 9 |
| front leg plant angle (°) | | | 39 ± 3 | 39 ± 2 | | |
| pelvis orientation – tilt (°) | 188 ± 7$^{**}$ | 192 ± 6 | ***170 ± 5***$^{***}$ | ***175 ± 4*** | 152 ± 10$^{*}$ | 155 ± 8 |
| pelvis orientation – drop (°) | 193 ± 7$^{**}$ | 189 ± 5 | 177 ± 5 | 176 ± 7 | 165 ± 6$^{*}$ | 168 ± 7 |
| pelvis orientation – twist (°) | 230 ± 12 | 228 ± 16 | 217 ± 10 | 217 ± 7 | 165 ± 12$^{*}$ | 168 ± 9 |
| lumbopelvic angle (°) | 167 ± 5$^{*}$ | 166 ± 6 | ***176 ± 5***$^{**}$ | ***172 ± 6*** | 162 ± 6 | 162 ± 7 |
| lumbopelvic angle – side flexion (°) | 179 ± 5$^{*}$ | 181 ± 7 | 163 ± 6$^{*}$ | 166 ± 4 | 174 ± 5$^{**}$ | 176 ± 4 |
| lumbopelvic angle – rotation (°) | 169 ± 11 | 171 ± 12 | 205 ± 10 | 206 ± 8 | 189 ± 7$^{*}$ | 187 ± 6 |
| thoracolumbar angle (°) | 187 ± 9 | 185 ± 11 | 183 ± 8 | 184 ± 9 | 158 ± 10$^{*}$ | 156 ± 11 |
| thoracolumbar angle – side flexion (°) | ***182 ± 8***$^{**}$ | ***179 ± 3*** | 188 ± 7$^{*}$ | 186 ± 7 | ***163 ± 4***$^{***}$ | ***160 ± 3*** |
| thoracolumbar angle - rotation (°) | ***177 ± 5***$^{***}$ | ***182 ± 4*** | 177 ± 6$^{*}$ | 178 ± 5 | 194 ± 4 | 194 ± 3 |
| lower thoraco-pelvic angle (°) | 166 ± 7$^{**}$ | 162 ± 9 | 178 ± 7$^{**}$ | 174 ± 8 | 140 ± 9$^{*}$ | 137 ± 7 |
| lower thoraco-pelvic angle – side flexion (°) | 179 ± 7$^{*}$ | 176 ± 8 | 163 ± 6 | 164 ± 5 | 166 ± 6 | 165 ± 3 |
| lower thoraco-pelvic angle – rotation (°) | 170 ± 9$^{*}$ | 173 ± 13 | 201 ± 6 | 201 ± 5 | 195 ± 6 | 195 ± 6 |

***Bold italic text denotes significant difference between injured and non-injured bowlers using an alpha value of 0.05.***

$^{***}$ large effect size (d ≥ 0.80, r ≥ 0.50), $**$ medium effect size (d ≥ 0.50, r ≥ 0.30), $^{*}$ small effect size ( d ≥ 0.20, r ≥ 0.10).

Two significant differences with medium effect sizes (d > 0.5, r > 0.3) were found in the parameters calculated in the transitions between BFC and BR (Table 3). The injured bowlers had on average less extension of their front hip and more ipsilateral pelvic drop. No significant differences were found in the kinetic parameters (Table 4).

**Table 3: Group means and standard deviations for selected parameters between BFC and BR of the fast bowling action for bowlers with and without a history of LBSI**

| | **Flexion/tilt** | | **side flexion/drop** | | **rotation/twist** | |
|---|---|---|---|---|---|---|
| **parameters** | **LBSI** | **non-LBSI** | **LBSI** | **non-LBSI** | **LBSI** | **non-LBSI** |
| minimum front knee angle (°) | 154 ± 16 | 156 ± 15 | | | | |
| maximum front knee angle (°) | 179 ± 9$^{*}$ | 182 ± 9 | | | | |
| front knee flexion (°) | 14 ± 2 | 14 ± 4 | | | | |
| shoulder counter rotation (°) | | | | | 43 ± 14 | 40 ± 20 |
| minimum front hip angle (°) | 109 ± 9$^{**}$ | 113 ± 6 | | | | |
| maximum front hip angle (°) | ***131 ± 9$^{**}$*** | ***137 ± 6*** | | | | |
| minimum pelvis orientation (°) | 150 ± 8$^{**}$ | 154 ± 7 | 165 ± 6$^{**}$ | 168 ± 7 | 164 ± 12$^{*}$ | 166 ± 8 |
| maximum pelvis orientation (°) | 191 ± 7$^{*}$ | 194 ± 5 | ***195 ± 8$^{**}$*** | ***190 ± 6*** | 247 ± 15$^{*}$ | 243 ± 14 |
| minimum lumbopelvic angle (°) | 161 ± 5 | 161 ± 6 | 161 ± 6$^{**}$ | 164 ± 5 | 165 ± 10$^{*}$ | 168 ± 12 |
| maximum lumbopelvic angle (°) | 179 ± 4$^{**}$ | 175 ± 6 | 182 ± 5 | 182 ± 7 | 207 ± 10 | 207 ± 8 |
| minimum thoracolumbar angle (°) | 158 ± 10 | 156 ± 11 | 159 ± 5$^{**}$ | 155 ± 6 | 173 ± 5$^{*}$ | 175 ± 5 |
| maximum thoracolumbar angle (°) | 192 ± 8 | 190 ± 10 | 190 ± 7$^{*}$ | 189 ± 6 | 203 ± 6 | 203 ± 7 |
| minimum lower thoraco-pelvic angle (°) | 139 ± 9$^{*}$ | 136 ± 7 | 146 ± 7$^{*}$ | 149 ± 6 | 166 ± 9$^{*}$ | 171 ± 12 |
| maximum lower thoraco-pelvic angle (°) | 181 ± 7$^{**}$ | 177 ± 7 | 178 ± 7$^{**}$ | 181 ± 6 | 208 ± 7$^{*}$ | 206 ± 7 |

***Bold italic text denotes significant difference between injured and non-injured bowlers using an alpha value of 0.05.***

$^{***}$ large effect size (d ≥ 0.80, r ≥ 0.50), ** medium effect size (d ≥ 0.50, r ≥ 0.30), $^{*}$ small effect size ( d ≥ 0.20, r ≥ 0.10).

The ten significant parameters were put forward as potential candidate variables for input into the binary logistic regression model. Following a bivariate correlation analysis, pelvis tilt orientation at FFC and maximum front hip angle were removed as candidate variables due to their collinearity with front hip angle at FFC ($r > 0.7$, $p < 0.01$). Similarly, thoracolumbar side flexion at BFC was removed as a candidate variable due to its collinearity with thoracolumbar rotation at BFC ($r > 0.7$, $p < 0.01$). All other significant correlations between candidate variables were below the 0.70 threshold and used to determine the best logistic regression model (Table 5).

**Table 4: Kinetic parameters derived from the ground reaction force of the front foot of the fast bowling action for bowlers with and without a history of LBSI**

| | (kN) | | (BW) | |
|---|---|---|---|---|
| **parameters** | **LBSI** | **non-LBSI** | **LBSI** | **non-LBSI** |
| peak horizontal force | -3.4 ± 0.9 | -3.6 ± 0.8 | -4.2 ± 1.1$^{*}$ | -4.4 ± 0.9 |
| peak vertical force | 5.6 ± 1.3 | 5.5 ± 0.8 | 6.9 ± 1.6 | 6.8 ± 1.0 |
| average horizontal loading rate | -136 ± 79$^{*}$ | -120 ± 40 | -166 ± 96$^{*}$ | -148 ± 49 |
| average vertical loading rate | 291 ± 209$^{*}$ | 216 ± 139 | 357 ± 258$^{*}$ | 272 ± 186 |
| horizontal impulse | -0.11 ± 0.03$^{*}$ | -0.12 ± 0.03 | -0.14 ± 0.03$^{*}$ | -0.15 ± 0.03 |
| vertical impulse | 0.14 ± 0.03 | 0.15 ± 0.04 | 0.18 ± 0.03 | 0.18 ± 0.04 |

$^{***}$ large effect size (d ≥ 0.80, r ≥ 0.50), ** medium effect size (d ≥ 0.50, r ≥ 0.30), $^{*}$ small effect size ( d ≥ 0.20, r ≥ 0.10).

The best logistic model included both the rear hip angle at BFC and the lumbopelvic angle at FFC, correctly classifying 88% of the fast bowlers in the appropriate injured or non-injured groups (Table 5). The inclusion of more than two parameters did not significantly improve the predictive ability of the regression model. The odds of a bowler sustaining a LBSI was negatively related to their rear hip angle at BFC, and positively related to their lumbopelvic angle at FFC. For each 1° increment in the rear hip angle at BFC, the odds of having a LBSI was a factor of 0.88 lower, while a 1° increment in the lumbopelvic angle at FFC increased the odds of a LBSI by 1.25 (Table 5).

The best logistic model was also explored to see how the two predictive variables influenced the odds of developing a prospective LBSI relative to the non-injured group. Using low risk values from a bowler within the study (rear hip angle at BFC = 170°; lumbopelvic angle at FFC = 170°) the odds ratio of a prospective LBSI was 0.1 (95% CI: 0.01 – 0.99, Figure 1a) compared to an odds ratio of 1.0 when using the mean of the non-injured group (rear hip angle at BFC = 156°; lumbopelvic angle at FFC = 172°, Figure 1b). Setting the rear hip angle at BFC to the mean of the injured bowlers (146°) and the lumbopelvic angle at FFC to the mean non-injured bowlers (172°) increased the odds of a prospective LBSI to 4.8 (95% CI: 1.6 – 14.0, Figure 1c).

Setting the rear hip angle to a high risk value demonstrated by a bowler in this study (123°) while maintaining the lumbo-pelvic angle at the mean of the non-injured bowlers (172°) increased the odds of a prospective LBSI to 88.9 (95% CI: 4.3 – 1854.2, Figure 1d). When inputting the mean injured lumbopelvic angle (176°) and the mean rear hip angle at BFC (146°) the odds ratio more than doubled from 4.8 to 11.5 (95% CI: 3.0 – 43.4) compared to when the non-injured mean lumbopelvic angle was used. Finally, when the lumbopelvic angle at FFC was set to a high risk value demonstrated by a bowler in this study (180°) while adopting a high risk rear hip angle at BFC (123°) the odds of sustaining a prospective LBSI increased to an odds ratio of 484.0 (95% CI: 23.1 – 10159.0).

**Table 5: Binary logistic regression models of 50 fast bowlers' LBSI injury history for biomechanical predictor variables**

| model | predictor | β (SE) | Wald's $X^2$ | *p* | $e^{\beta}$ (odds ratio) | $e^{\beta}$ 95% C.I | Overall % correct |
|---|---|---|---|---|---|---|---|
| 1 | rear hip angle at BFC | -0.11 (0.04) | 6.62 | 0.01 | 0.90 | 0.83 – 0.98 | 76 |
| | constant | 17.5 (6.4) | 7.43 | | | | |

*Cox & Snell $r^2 = 0.16$; Nagelkerke $r^2 = 0.24$; Hosmer & Lemeshow: $\chi^2(8) = 14.8$, $p = 0.06$;*
*Model $\chi^2(1) = 8.6$, $p < 0.01$*

| model | predictor | β (SE) | Wald's $X^2$ | *p* | $e^{\beta}$ (odds ratio) | $e^{\beta}$ 95% C.I | Overall % correct |
|---|---|---|---|---|---|---|---|
| 2 | rear hip angle at BFC | -0.13 (0.05) | 6.64 | 0.01 | 0.88 | 0.80 – 0.97 | 88 |
| | lumbopelvic angle at FFC | 0.23 (0.10) | 5.40 | 0.02 | 1.25 | 1.04 – 1.52 | |
| | constant | -18.7 (16.1) | 1.35 | | | | |

*Cox & Snell $r^2 = 0.27$; Nagelkerke $r^2 = 0.41$; Hosmer & Lemeshow: $\chi^2(8) = 12.2$, $p = 0.14$;*
*Model $\chi^2(2) = 15.5$, $p < 0.01$*

## DISCUSSION

The aim of this study was to investigate the technique characteristics that distinguished between elite cricket fast bowlers with and without a history of LBSI. The results are the first to demonstrate significant differences in technique between fast bowlers who have and have not experienced a prospective LBSI. Bowlers with high amounts of rear hip flexion at BFC and lumbopelvic extension at FFC have a substantially increased likelihood of developing a LBSI (Table 5).

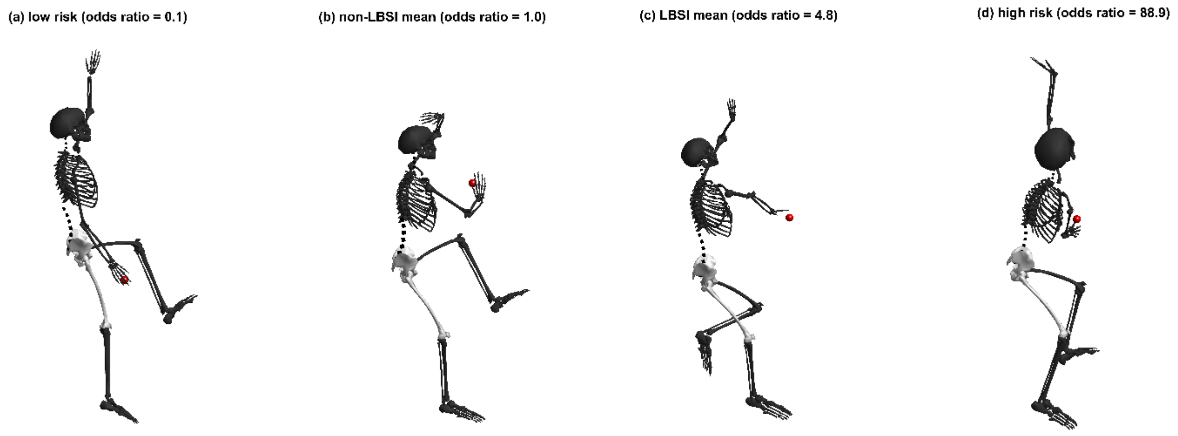

**Figure 1: Odds ratios of experiencing LBSI for representative rear hip angles at back foot contact (lumbopelvic angle at FFC): a) 170° (170°), b) 156° (172°), c) 146° (172°) and d) 123° (172°) viewed perpendicular to the hip joint centre**

The best single independent predictor of prospective LBSI injury was the angle of the rear hip at BFC which successfully categorised the injury history of 76% of the bowlers in this study (Table 5). Previous research has suggested that the role of the rear leg during the transition from BFC to FFC is to maintain the linear momentum developed in the run-up (Felton et al., 2019). The efficiency of this phase is likely to be related to the velocity of the centre of mass at BFC, the strength of the bowler and their initial kinematics at BFC. This study indicates that adopting a position with increased flexion of the rear hip and rear knee angles at BFC (Table 2) substantially increases the likelihood of developing a LBSI. Although the cause for adopting this injurious position was not identified within this study, previous research has linked poor pelvi-femoral control and single leg stability with LBSI in fast bowlers (Bayne et al., 2016; Olivier et al., 2015). This may indicate that the initial kinematics adopted at BFC are dictated by a requirement to produce joint torques to stabilise the pelvis and control the momentum from the run-up. Although the adoption of a technique with rear hip and knee joint angles closer to the mid-range of the joint may allow for greater extensor torques to be produced (Thorstensson et al., 1976), it may still be insufficient to stabilise the pelvis and control the momentum from the run-up. Future research should focus on understanding the cause and effect of factors, such as centre of mass velocity and rear leg strength, on the initial kinematics at BFC to inform coaching practice.

The next-best independent predictor, when included with the rear hip angle at BFC, of prospective LBSI injury was the lumbopelvic angle at FFC which successfully categorised the injury history of 88% of the bowlers in this study when considered alongside the rear hip angle at BFC (Table 5). Despite a high incidence of LBSI in other sports with repetitive lumbar flexion and extension (Tawfik et al., 2020), previous research investigating the aetiology of LBSI in fast bowlers have not explored the flexion-extension kinematics of the lower back, although a significantly greater peak lumbopelvic flexion-extension moment has been observed in fast bowlers who prospectively sustained a lower back injury compared to their uninjured counterparts (Bayne et al., 2016). The current study suggests that bowlers who exhibit more lumbopelvic extension at FFC have a greater likelihood of developing a LBSI, which may be as a result of the greater lumbopelvic moment previously observed (Table 5). It is important to consider this finding within the wider context of the lumbo-pelvi-femoral complex at FFC. At FFC, bowlers who suffered a prospective LBSI also had significantly more anterior pelvic tilt and significantly smaller front hip angles compared to the non-injured group (Table 2). They also exhibited greater ipsilateral pelvic drop between BFC and BR (Table 3). These differences suggest that the injured bowlers were less successful in stabilising their pelvis during the transition from BFC to FFC, which may be indicative of poor pelvi-femoral control (Bayne et al., 2016). It is proposed that bowlers with more anteriorly tilted pelvis orientations at FFC compensate by extending at the lumbopelvic junction. This allows the upper spinal column to be positioned optimally to maximise trunk flexion from FFC to BR, a characteristic previously linked with increased ball release speeds (Worthington et al., 2013). Alternatively, it is possible that extension of the lumbopelvic angle could be as a consequence of impaired lumbo-pelvic control (Bayne et al., 2016).

These two predictor variables in the logistic regression provide an indication of the likelihood of a LBSI when multiple risk factors are present. The more flexed rear hip angles at BFC employed by the injured bowlers more than quadrupled the odds of a prospective LBSI being sustained. When the rear hip angles were utilised in combination with greater extension of the lumbopelvic junction odds of a prospective LBSI increased by a factor greater than 11. Although LBSI's are multifactorial in nature (Warden et al., 2006), this provides evidence that technique independently increases the odds of sustaining a prospective LBSI. Mixed bowling actions have previously been widely considered as the cause of LBSI (Elliott et al., 1992; Foster et al., 1989; Portus et al., 2004), despite the two-dimensional nature and disparity in identifying the instant of BFC leading to contradictory findings (Senington et al., 2018). This study found no link between shoulder-counter rotation, pelvis-shoulder separation at BFC or the shoulder twist orientation at BFC, and LBSI (Tables 2 and 3). Significant differences were found however at BFC in the thoracolumbar side flexion and rotation angles (Table 2), where thoracolumbar rotation may contribute to thoraco-pelvic rotation (the three-dimensional equivalent of the pelvis-shoulder separation angle). Bowlers who experienced prospective LBSI were ipsilaterally side flexed and contralaterally rotated at BFC compared to their non-injured counterparts who were contralaterally side flexed and ipsilaterally rotated (Table 2).

No comparison or similarities however can be drawn between these findings and the definition of a mixed action.

Excessive lateral trunk side flexion during the transition from FFC to BR has also been linked with LBSI (Bayne et al., 2016; Ranson et al., 2008). Contralateral trunk side flexion occurs during cricket bowling to increase the height of the hand at ball release. The findings of this study suggest bowlers with LBSI adopt different lumbopelvic and thoracolumbar side flexion kinematics to achieve similar amounts of spinal contralateral side flexion (Tables 2 and 3). Bowlers who develop LBSI were found to have less contralateral thoracolumbar side flexion compared to the non-injured bowlers at BR (Table 2). While this contradicts previous findings, to have similar levels of thoraco-pelvic contralateral side flexion at BR the injured bowlers theoretically must exhibit greater amounts of contralateral lumbopelvic side flexion compared to their non-injured counterparts. Although the differences in the lumbopelvic side flexion angle at BR were not significant at the 0.05 alpha level ($p = 0.09$), a medium effect size ($d = 0.57$) was observed indicating that this difference could be important. This study provides evidence that bowlers with LBSI have a greater contribution to trunk side flexion at the lumbopelvic junction rather than the thoracolumbar junction (Table 2). The cause of this increased contralateral side flexion at the lumbopelvic joint in the bowlers who experience LBSI is unknown. While it may be as a direct consequence of the increased rear hip flexion at BFC which has been associated with increased frontal plane movement of the lumbar spine in single leg landing tasks (Popovich and Kulig, 2012), it may also be linked to the musculature surrounding the lumbar spine being unable to resist contralateral lumbopelvic side flexion (Campbell et al., 2016). Future research should focus on identifying the causes which results in an increase in contralateral side flexion at the lumbopelvic junction. In particular, a theoretical approach could be adopted to understand how lumbopelvic and pelvi-femoral control affects the muscular loading on the lumbopelvic region.

Kinetic parameters and their kinematic predictors have also been proposed as potential factors in LBSI in fast bowlers. Ranson et al. (Ranson et al., 2008) has previously suggested that the extreme contralateral side flexion of the lower thoracic spine (T10 to L1) relative to the pelvis in combination with large ground reaction forces, is the most significant stressor of the contralateral side lumbar neural arch. The results of this study show no difference in the ground reaction force parameters, both in overall magnitude or normalised to bodyweight, between bowlers with and without prospective LBSI. This indicates that the large ground reaction forces experienced in fast bowling may not independently contribute to LBSI but may contribute in combination with lumbar kinematics which are known to increase stress on the neural arch of lumbar vertebra (Chosa et al., 2004).

The pars interarticularis have been reported to be under the greatest stress when compression is combined with lumbar extension, lumbar side-flexion and lumbar rotation (Chosa et al., 2004). Further, extension of the lumbar spine has been estimated to increase stresses upon the distal-ventral region of the pars interarticularis, where LBSI’s originate (Terai et al., 2010). The injured bowlers in this study have greater lumbopelvic extension at FFC and greater contralateral lumbopelvic side-flexion at BR providing a pathomechanical basis for the unique unilateral presentation of LBSI in elite fast bowlers. These findings agree with research in other sports with high incidences of LBSI (Tawfik et al., 2020) where extension of the lumbar spine in combination with lumbar rotation is suggested to be a mechanism of LBSI. The current results suggest that the combination of lumbopelvic extension and contralateral side flexion contribute to bone strains within the contralateral neural arch of the lower lumbar spine. It is likely that these are above the microdamage thresholds of the bone, accelerating accumulation and propagation (Frost, 2003), reducing the number of cycles which an individual can tolerate before sustaining a LBSI. While this research confirms Ranson et al.'s (2008) belief that the pathomechanics of LBSI are not related to action classification, they concluded that the likely mechanical aetiology is the motion of the lower thorax relative to the pelvis. The findings of this study highlight however that it is the motion at the lumbopelvic junction, which is adjacent to the site of typical LBSI (Alway et al., 2019) , that is the likely mechanical aetiology. Future biomechanical analysis on fast bowlers should focus on the lumbopelvic junction when considering LBSI risk.

While the aim of this study was not to identify the factors which are linked to the injurious lumbopelvic motion exhibited by fast bowlers with LBSI, the results highlight lumbopelvic and pelvi-femoral control as a potential cause. The position adopted by the injured bowlers in this study at BFC with more flexed hip and knee angles, has previously been discussed as a potential mechanism to produce adequate torque to stabilise the pelvis and redirect the centre of mass during the transition from BFC to FFC. Bowlers who adopt this injurious rear leg technique to maximise torque production either do so due to athlete-specific strength constraints e.g. a developing young fast bowler, or task-specific strength requirements e.g. to redirect a poorly aligned centre of mass velocity at BFC. The significant differences in the thoracolumbar angles at BFC, where the injured bowlers were in ipsilateral side flexion and contralateral rotation compared to the non-injured bowlers who were in contralateral flexion and ipsilateral rotation, could also be explained by a poorly aligned centre of mass velocity. While previous research has shown faster run-ups are known to correlate with increased ball release velocity (Worthington et al., 2013), an optimum run-up speed must exist for each bowler beyond which technique begins to fail. The observed kinematics in this study, which identifies bowlers with LBSI with a potential inability to stabilise their lumbo-pelvi-femoral complex, could also result from a run-up which is potentially mis-aligned or beyond its optimum, requiring torque production in excess of the bowler's current capabilities to stabilise the lumbo-pelvi-femoral complex. In the future, research is required to understand the cause and effect relationships of centre of mass velocity on the kinematics and kinetics of the transition from BFC to FFC and LBSI to develop coach education and reduce LBSI occurrence in fast bowlers.

A major strength of this research is the large number of elite fast bowlers, as well as the prospective injury history and radiological screening of all players involved. However, whilst both samples represent the groups from which they have been recruited, the population size of elite fast bowlers with a history of LBSI is much larger compared to non-injured bowlers. This led to the difference in sample sizes in this study which could potentially skew the technique associated with LBSI and result in a sample size bias (Chu et al., 2009). Further limitations include adopting a discrete rather than a continuous approach to analysing the data, which investigates key time points rather than the whole movement pattern, and the use of absolute angles rather than relative angles normalised to the participants range of motion, which may elicit further information on the aetiology of LBSI in fast bowlers. Finally, multiple comparisons between groups were made without an adjustment to the alpha level since it increases the incidence of Type 2 errors (Sinclair et al., 2013). These comparisons should be considered cautiously as an increased risk of Type 1 errors occurring remains, but findings of the main logistic regression analysis are not compromised by multiple testing

## CONCLUSION

This study is the first to demonstrate significant differences in technique between fast bowlers who have and have not experienced a prospective LBSI. Lumbopelvic extension at FFC and contralateral side flexion at BR were significantly greater in bowlers who prospectively sustained LBSI. The rear hip angle at BFC was observed to be the best predictor of LBSI in this study, potentially identifying task-specific or athlete-specific strength constraints, which may indicate poor lumbo-pelvi-femoral complex control as the cause. The results of this research are likely to be useful in aiding identification of fast bowlers at risk of LBSI, as well as enhancing coaching and rehabilitation of fast bowlers from LBSI. Coach education should incorporate these findings and move away from using far removed derivatives to inform practice which are not consistent with predicting LBSI injury. Future research should attempt to understand the cause and effect of strength constraints on the predictors of LBSI and develop an understanding of the muscular forces acting on the lumbo-pelvi-femoral complex during fast bowling.

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