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

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Abstract

Lower back injuries, specifically lumbar stress fractures, account for the most lost playing time in professional cricket. The aim of this study was to investigate the relationship between the current fast bowling action classification system and potentially injurious kinematics of the lower trunk during fast bowling. 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. Seventy-four percent of the fast bowlers used a mixed bowling action attributable to having shoulder counter-rotation greater than 30°. There was no 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. The greatest proportion of lower trunk extension (26%), contralateral side-flexion (131%) and ipsilateral rotation (79%) was utilised during the front-foot contact phase of the fast bowling delivery stride. It is proposed that the combination of end range lower trunk positioning, especially side-flexion, and high ground reaction (compressive) forces during the front foot contact phase are the most important pathomechanical factors in the typical pattern of contralateral side lumbar stress injuries seen in this population.

Keywords: fast bowling, cricket, trunk kinematics, lower back injuries

Introduction

Lower back injuries to fast bowlers in cricket results in the greatest amount of lost playing time amongst professional cricketers (Orchard *et al.*, 2002, Newman, 2003). Lumbar stress injuries (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 (Elliott *et al.*, 1992, Ranawat *et al.*, 2003, Gregory *et al.*, 2004, Ranson *et al.*, 2005). In addition, a unique pattern of multi-level, non-dominant side, chronic pars interarticularis stress reactions are highly prevalent in this population, and when compared to age-matched athletic individuals, fast bowlers have a higher prevalence of multiple level lumbar disc degeneration (Ranson *et al.*, 2005).

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 (Elliott *et al.*, 1986, Foster *et al.*, 1989, Elliott *et al.*, 1992, Elliott *et al.*, 1993, Burnett *et al.*, 1995, Burnett *et al.*, 1996, Elliott and Khangure, 2002, Portus *et al.*, 2004). It is believed that the development of lower back injury in fast bowlers is multifactorial, although, fast bowling technique has been the predominant area of investigation due the reported relationship between specific aspects of fast bowling technique and the appearance of radiological abnormalities (Elliott *et al.*, 1992, Elliott *et al.*, 1993, Burnett *et al.*, 1996).

The fast bowling action begins during the delivery stride prior to ball release. The first critical event during the delivery stride is back foot contact (BFC) when the bowler's back foot impacts the ground. This is followed by front-foot contact (FFC) then ball release (BR). 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 BFC and the amount of shoulder counter-rotation (SCR) during the delivery stride (Elliott *et al.*, 1992, Burnett *et al.*, 1995, Clarke and Morris, 1996, Portus *et al.*, 2004). SCR is defined as the change in the shoulder alignment angle from a relatively front-on alignment at BFC (Figure 1a) to the most side-on shoulder alignment (Figure 1b) during the delivery stride (minimum shoulder angle). Several classification systems have been described in the literature with SCR thresholds for the mixed action being as low as 10° (Elliott *et al.*, 1992, Glazier *et al.*, 2000) and as high as 40° (Foster *et al.*, 1989). The fast bowling classification systems currently in use within the cricket associations in the United Kingdom and Australia state that any bowler that has greater than 30º SCR is classified as having a mixed action (Clarke and Morris, 1996, Portus *et al.*, 2004). Further, when measuring shoulder and pelvic alignment, bowlers can be classified as having a mixed action when the pelvic to shoulder separation angle at BFC exceeds 30º (Stockhill and Bartlett, 1992, Burnett *et al.*, 1995, Portus *et al.*, 2004).

a **b** **c** **d**

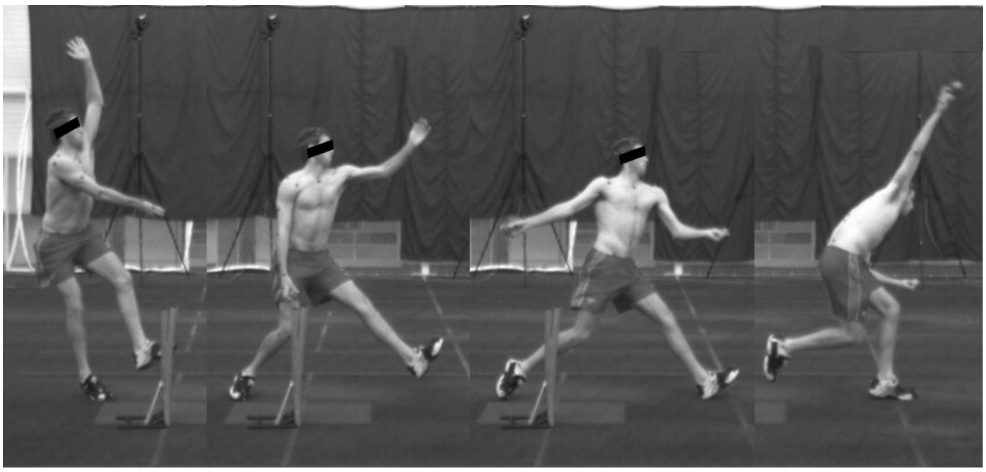

Figure 1. The delivery stride of fast bowling a) Back foot contact b) Minimum shoulder angle c) Front foot contact d) Ball release.

Several studies have reported an association between lower back injury and the mixed bowling action (Foster *et al.*, 1989, Elliott *et al.*, 1992, Elliott *et al.*, 1993, Burnett *et al.*, 1996). Specifically, Portus *et al.* (2004), in a retrospective study of elite Australian fast bowlers, reported that bowlers who previously suffered lower back soft tissue injuries had non-significantly larger pelvic to shoulder separation angles at BFC. Furthermore, SCR values were found to be significantly higher in bowlers who had suffered lumbar stress fractures when compared to non trunk-injured bowlers. However, the precise mechanism behind the relationship between high SCR and elevated rates of lumbar spine stress in mixed action bowlers is presently unknown. To date, only one study (Burnett *et al.*, 1998), has investigated aspects of the 3D kinematics of the lower trunk spine during fast bowling. This study revealed that although variables used to classify fast bowling action type occurred between BFC and FFC, the movements most likely to place the greatest mechanical load on the lumbar spine occurred between FFC and BR. Coincidently, this is also the phase of the bowling action where peak ground reaction forces are produced (Elliott *et al.*, 1986, Foster *et al.*, 1989, Hurrion *et al.*, 2000).

Chosa *et al.* (2004) 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 ROM of lumbar axial rotation is reduced when the spine is in end range extension (Haberl *et al.*, 2004, Burnett *et al.*, 2006), therefore implying increased stiffening of the spine when it is positioned near the limits of its physiological ROM. Panjabi (1992) 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 FFC, 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 investigate the relationship between the current fast bowling action classification system and potentially injurious kinematics of the trunk during fast bowling. Trunk kinematic variables included those used to classify bowling action type i.e. shoulder and pelvic alignment, along with the proportion of lower trunk extension, side-flexion and axial rotation utilised during the delivery stride of fast bowling.

Methods

Subjects 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. Subjects were considered as fast bowlers by the England Cricket Board fast bowling coaches. The mean (± s) age, height and weight of the subjects was 23 ± 4 years, 1.86 ± 0.05m and 86 ± 8kg respectively. Subjects 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.

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 (ROM) 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 subjects to bowl with their normal length run-up on a standard size artificial cricket pitch (Figure 2). Cameras were positioned around the bowling crease to cover a 7m × 3m × 3m volume which was wand calibrated prior to data collection.

Figure 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 where used to quantify lower trunk kinematics during the ROM 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 subjects were given adequate time for their routine pre-bowling warm-up activities which included several warm-up deliveries.

For the standing ROM 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.” Subjects then practised this motion so that the investigators were confident that they were moving to the end of their trunk ROM in each direction.

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 ROM trial. The instants of back foot contact (BFC) (Figure 1a) and front foot contact (FFC) (Figure 1c) were defined as the first image where the appropriate foot came in contact with the ground based upon visual inspection of the horizontal time histories of the heel and toe markers. Ball release (BR) was defined as the image closest to release of the ball (Figure 1d).

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 (Figure 3).

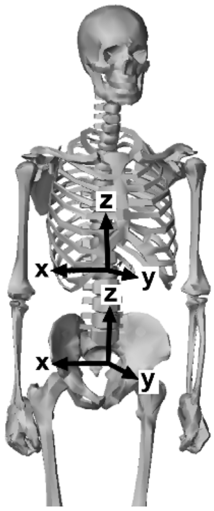

Figure 3. Local orthogonal reference frames for the pelvis and lower thorax used to determine lower trunk kinematics.

Bowling Action Classification

The bowling action of each subject was classified as one of four bowling types according to the shoulder angle and pelvic to shoulder separation angle (Table 1). 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 (Stockhill and Bartlett, 1992, Burnett *et al.*, 1995, Portus *et al.*, 2004). 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 (180º = side-on, 270º = shoulders aligned with the bowling crease). The pelvic angle was determined by projecting the X-axis of the pelvic reference frame onto a horizontal plane (180º = side-on, 270º = pelvis aligned with the bowling crease). The pelvic to shoulder separation angle was then defined as the shoulder angle minus the pelvic angle (Burnett *et al.*, 1995, Burnett *et al.*, 1998, Portus *et al.*, 2004).

Table 1. Fast bowling action classification variables and their typical values used to define fast bowling action types (Portus *et al.*, 2004)

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

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 ROM and bowling trials (Cole *et al.*, 1993, Burnett *et al.*, 1998). A 'neutral' upright anatomical position was identified for each bowler in the ROM 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 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, (Chosa *et al.*, 2004) were determined for the ROM trial, and each bowling trial.

The time histories of each kinematic descriptor were fitted using quintic splines (Wood and Jennings, 1979). 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 (Yeadon and King, 2002).

Reliability of the Kinematic Variables

Intra-class correlation (ICC), and relative SEM (%SEM) statistics (Norton *et al.*, 2000) were calculated to determine the inter-trial variability of each of the variables used to determine the bowling action type, 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 subject.

All action classification and trunk kinematic variables had high ICC values (range 0.86 - 0.97) (Table 2). Low %SEM values were found for all variables (range 1.5 - 9.1) apart from, pelvic to shoulder separation at BFC and lower trunk extension which had moderate %SEM values (18.8 & 17.2 respectively) (Table 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 was (1.6°, range 1.1° - 2.9°). As a result of the high reliability of these variables, 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 trails was then expressed as a percentage of the maximum ROM achieved during the ROM trial

Table 2. Reliability indices (ICC and %SEM) for variables used to determine fast bowling action type and trunk kinematic variables of interest. All mean (s) data are in degrees.

Kinematics	Variable	Mean° (s)	ICC	%SEM
Action Classification	Shoulder Angle at Back Foot Contact	234 (18)	0.97	1.5
	Minimum Shoulder Angle	194 (10)	0.9	1.5
	Shoulder Counter-Rotation	41 (16)	0.97	6.7
	Back Foot Contact Pelvic-Shoulder Separation	23 (13)	0.89	18.8
Lower Trunk	Extension	9 (6)	0.93	17.2
	Contralateral Side-Flexion	34 (7)	0.88	6.7
	Ipsilateral Rotation	32 (8)	0.86	9.1
Whole Trunk	Maximum Pelvic-Shoulder Separation	45 (9)	0.93	5.3

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

Statistical analysis

Independent t-tests were used to determine if there was any difference in the proportion of lower trunk ROM utilised by mixed and non-mixed action (front-on, midway and side-on) bowlers. Non-mixed action bowlers were pooled as these action types have previously been considered 'safer' for the lower back than the mixed action (Foster *et al.*, 1989, Burnett *et al.*, 1996, Burnett *et al.*, 1998, Elliott and Khangure, 2002). Effect sizes were also calculated for this comparison with effect sizes of less than 0.2 considered small, 0.2 to 0.5 medium and 0.5 to 0.8 large (Cohen, 1988). Further, Pearson's product moment correlation coefficients were used to determine whether any association was evident between SCR 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 (Johnston, 2000) . All analyses were conducted using SPSS V11.0 for Windows (SPSS Inc., Chicago, Illinois). The level of statistical significance was set at $p<0.05$.

Results

For the purposes of this study only shoulder angle at BFC and the magnitude of SCR were used to classify the type of bowling action utilised as the third variable used to classify action type, pelvic to shoulder separation at BFC, has been shown not to be associated with pars interarticularis stress injury in fast bowlers (Portus *et al.*, 2004). Using the above criteria, 39 of the 50 bowlers (78%) were determined to have used a mixed action, while nine eight (16%) used a mid-way action and three (6%) used a side-on action. No bowler was deemed to have used a front-on bowling action. It should be noted that if pelvic to shoulder separation at BFC was included as an action classification criteria there would have been little difference in the number of bowlers in each action type. Specifically, only a further two of the midway bowlers would have been classified as mixed as they had a pelvic to shoulder separation at BFC of over 30°.

The percentage of lower trunk extension, contralateral side-flexion and ipsilateral axial rotation used by bowlers of each action type is displayed in Table 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 when compared to the non-mixed action bowlers (Table 3) although large effect sizes were found for contralateral lower trunk contralateral side-flexion (d=0.66) and ipsilateral rotation (d=0.57). Also, there was no difference (t = 0.117, p=0.91) in the minimum shoulder angle obtained by the mixed (mean 194°, s=9) and non-mixed action (mean 193°, s=11) bowlers.

Table 3. Mean (s) of available 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. All mean (s) data are in degrees.

	Mean (s) percentage of lower trunk ROM					
Action Type	Extension		Contralateral Side-Flexion		Ipsilateral Rotation	
Mixed	27	(21)	136	(36)	81	(19)
Midway	14	(17)	118	(27)	76	(23)
Side-on	38	(16)	108	(34)	52	(13)
All Non-mixed	20	(19)	115	(28)	69	(23)
All bowlers	26	(21)	131	(35)	79	(20)
Mixed v Non Mixed (*t* value)	0.978		1.757		1.792	
Mixed v Non Mixed (*P* value)	0.33		0.09		0.08	
Effect Size (*d* value)	0.35		0.66		0.57	

NB. *Statistical comparison was only conducted between the groups shown in bold*

A strong correlation (r = 0.86, p=0.00) was found between the shoulder angle at BFC and the magnitude of SCR. Further, there was a moderate correlation between the pelvic to shoulder separation angle at BFC and shoulder alignment at BFC (r = 0.52, p=0.00), along with a weak correlation between pelvic to shoulder separation angle at BFC and SCR (r = 0.44, p=0.00). A significant, weak correlation was found between SCR and ipsilateral lower trunk rotation (r = 0.34, p=0.02). There was no correlation between SCR and the proportion of lower trunk extension or side flexion. Furthermore, no correlation was found between the pelvic to shoulder separation angle at BFC and the proportion of ROM of the lower trunk kinematic variables of interest (Table 4).

Table 4. Correlations, r (P value), between Shoulder Counter-Rotation and the Pelvic to Shoulder Separation angle at Back Foot Contact (BFC), and the lower trunk kinematic variables of interest. Significant Correlations in bold.

	%ROM Extension	%ROM Contralateral Side Flexion	%ROM Ipsilateral Rotation	Shoulder Angle at Back Foot Contact	Shoulder Counter-Rotation
Shoulder Counter-Rotation	-0.04 (0.78)	0.18 (0.21)	0.34 (0.02)	0.86 (0.00)	-
Pelvic to Shoulder Separation at BFC	-0.21 (0.15)	0.14 (0.32)	0.19 (0.19)	0.52 (0.00)	0.44 (0.00)

The minimum shoulder angle typically occurred just prior to FFC whilst the maximum pelvic to shoulder separation occurred, on average, 0.03 seconds after FFC (Figure 4a). Maximum lower trunk extension took place, on average, 0.01 seconds after FFC 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 FFC respectively (Figure 4b).

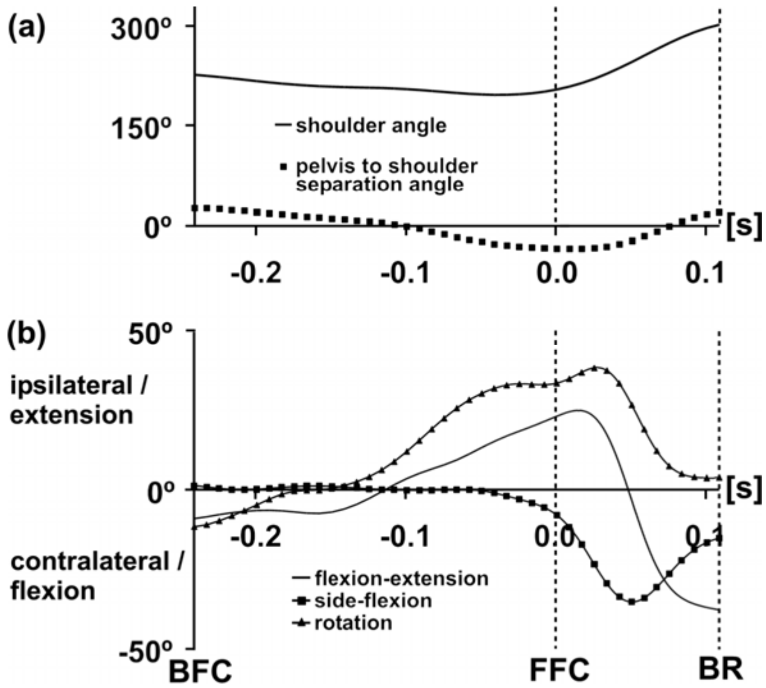

Figure 4. a) Typical shoulder angles and pelvic to shoulder separation angles, and b) lower trunk flexion-extension, side-flexion and rotation angles during the delivery stride of fast bowling. Delivery stride events are back foot contact (BFC), front foot contact (FFC) and ball release (BR).

Discussion

Originally, fast bowling classification systems were designed to broadly describe bowling technique and biomechanical factors affecting performance (Elliott and Foster, 1984, Elliott *et al.*, 1986). However, these systems have evolved in an attempt to identify fast bowlers at risk of low back injury (Foster *et al.*, 1989, Burnett *et al.*, 1996, Portus *et al.*, 2004). 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 (Orchard *et al.*, 2002, Newman, 2003). In addition, the mechanism by which supposedly dangerous action types result in excessive stress on the contralateral side lumbar pars interarticularis is unclear.

The aim of this study was to investigate the relationship between variables used in the fast bowling action classification system currently employed in the United Kingdom (Clarke and Morris, 1996) and Australia (Portus *et al.*, 2004) and potentially injurious kinematics of the lower trunk during fast bowling. As reported in other studies that have used a similar classification system (Elliott and Khangure, 2002, Gray *et al.*, 2003, Portus *et al.*, 2004), a high proportion of the professional fast bowlers in this study were deemed to use what is currently considered to be an unsafe action type i.e. the mixed action. Further, 78% of bowlers were classified as having a mixed action (SCR > 30°) because they had high SCR, a variable previously associated with lumbar stress fracture (Foster *et al.*, 1989, Elliott *et al.*, 1992, Portus *et al.*, 2004). If the intent of action classification systems is to identify 'at risk' bowlers, the current system is unlikely to be able to sensitively identify those at increased risk of lumbar stress injury due to the large number of bowlers using a mixed technique.

In this study all bowlers tended to adopt a relatively side-on alignment of the shoulders just prior to FFC (Figure 1b) regardless of shoulder alignment (front-on, midway or side-on) at BFC (Figure 1a). The implication of this is that under the current action classification system the front-on classification appears redundant as all 16 bowlers in this study who had a front-on shoulder alignment at BFC had SCR greater than 30° and were therefore classified as 'mixed'. Based on the above findings, a review of the current methods of identifying potentially dangerous bowling technique should be considered.

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 (Chosa *et al.*, 2004). The current action classification variables; shoulder angle at BFC, pelvic to shoulder separation at BFC and SCR, are measured during the BFC to FFC phase. In this phase the lower trunk is typically positioned in a relatively neutral posture when compared to just prior to FFC and through to ball release (Figures 1 & 3b). Contact forces on the contralateral facet joints of the lumbar spine are likely to be low between BFC and FFC as the front foot is not in contact with the ground. Temporal analysis revealed that maximal lower trunk extension, side-flexion and rotation typically occur just after FFC (Figure 4b). Therefore, the combination of these trunk kinematics and high ground reaction forces that occur just after FFC (Elliott *et al.*, 1986, Foster *et al.*, 1989, Hurrion *et al.*, 2000, Portus *et al.*, 2004) are likely to result in maximal stresses on the contralateral side lumbar pars interarticulari during this phase of the bowling action. In accordance with the findings of Burnett *et al.* (1998), bowlers in this study with greater than 30° SCR did not use a significantly greater proportion of lower trunk extension, ipsilateral rotation and contralateral side-flexion when compared to non-mixed action bowlers. Therefore, there does not appear to be a pathomechanical basis for large SCR resulting in increased risk of stress injury to the contralateral side lumbar spine pars interarticularis.

Hyperextension of the lumbar spine is thought to be the mechanism of injury in other sports with a high rate of lumbar stress fractures such as gymnastics (Sward, 1992) and American Football (Ferguson *et al.*, 1974). Previous authors have suggested that excessive SCR may force the lumbar spine into hyperextension (Annear *et al.*, 1989, Elliott *et al.*, 1992, Bartlett, 2003). However, fast bowlers in this study utilised only a relatively small proportion of their available lower trunk extension ROM (26%) which questions the importance of this movement in the aetiology of lumbar stress injuries within this population.

The greatest proportion of lower trunk ROM utilised by the fast bowlers in this study was in contralateral side-flexion. During the FFC phase of the delivery stride fast bowlers utilised approximately 1.3 times the amount of side-flexion they obtained during the standing ROM 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 (Burnett *et al.*, 2006). Therefore, it might be concluded that this position of extreme contralateral lower trunk side-flexion, in combination with large ground reaction forces, is the most significant stressor of the contralateral side lumbar pars interarticulari (Panjabi, 1992, Chosa *et al.*, 2004).

SCR during the delivery stride of fast bowling has previously been proposed to be an indicator of spinal torsional stress (Foster *et al.*, 1989, Elliott *et al.*, 1993, Elliott *et al.*,

2002) and in this study a significant correlation, albeit weak, was found between SCR and the proportion of ipsilateral lower trunk rotation. However, using SCR to directly estimate the degree of torsional stress in the lumbar spine may be problematic. This is due to the fact that SCR is a significantly removed derivative of whole trunk rotation (Stockill and Bartlett, 1996) which occurs during the BFC to FFC phase of the bowling action whilst maximal lower trunk rotation occurs much later. Specifically maximal ipsilateral trunk rotation occurs, during the FFC to BR phase when the shoulders are rotating towards the contralateral side (Figure 4). Furthermore, a mechanical modelling study has indicated that rotational stresses alone are unlikely to be the major pathomechanical factor in lumbar stress injury (Chosa *et al.*, 2004). Additionally, in comparison to contralateral side-flexion, the proportion of ipsilateral lower trunk rotation utilised by fast bowlers was relatively low (79% versus 131%). This again suggests a greater importance of side-flexion than rotation or extension in the production of contralateral side lumbar pars interarticularis stress.

Maximum contralateral side-flexion, coupled with extension and ipsilateral rotation, coincides with large ground reaction (compressive) forces that occur soon after FFC (Elliott *et al.*, 1986, Foster *et al.*, 1989, Hurrion *et al.*, 2000, Portus *et al.*, 2004). This combination of lower trunk movements is the likely mechanical aetiology of the high prevalence of stress injuries that occur in the contralateral low lumbar spine of fast bowlers (Elliott *et al.*, 1992, Gregory *et al.*, 2004, Ranson *et al.*, 2005). The likely pathomechanics of lumbar stress injuries in fast bowlers does not appear to be primarily related to excessive SCR, the action characteristic previously reported to be related to low back injury (Elliott *et al.*, 1992, Burnett *et al.*, 1996, Elliott and Khangure, 1999, Portus *et al.*, 2004). Prevention of low back injuries in fast bowlers in cricket may require coaches to pay greater attention to spinal positioning during the FFC phase of the delivery stride, especially the magnitude of contralateral side-flexion.

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. Further, fast bowling action characteristics currently used to identify potentially dangerous action types do not appear to be directly related to the likely pathomechanics of contralateral side lumbar stress injuries. It is proposed that extreme lower trunk kinematics, especially contralateral side-flexion, during the early part of the FFC phase of the bowling action is likely to be the most important mechanical factor in the aetiology of this type of injury. However, prospective studies are required to determine the relationship between lower trunk kinematics and lumbar spine stress injuries in fast bowlers.

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