<u>**Title Page**</u>

Full Title

Are shoulder counter rotation and hip shoulder separation angle representative metrics of three-dimensional spinal kinematics in cricket fast bowling?

Running Title

Comparison of shoulder counter-rotation and fast bowling spinal kinematics.

Keywords

Spine; kinematics; cricket fast bowling; inertial sensors; correlation.

Journal Title

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Abstract

This study aimed to investigate the relationship between shoulder counter-rotation (SCR), hip shoulder separation (HSS) and three-dimensional spinal kinematics during fast bowling in cricket. Thirty five elite male fast bowlers were analysed using three-dimensional inertial sensors on the spine. Lumbar, thoracic and thoracolumbar kinematics were determined during the delivery stride. Spearman's pairwise correlations displayed significant associations between SCR, thoracic and thoracolumbar lateral flexion between the back foot impact and max contralateral rotation phase of the delivery stride (r_s=-.462 and -.460). HSS and thoracolumbar lateral flexion displayed a significant correlation between back foot impact and max contralateral rotation (r_s=-.552). No other significant correlations were observed. These results suggest SCR and HSS are modestly related to lateral flexion, leaving a large component of SCR and HSS unrelated to specific three-dimensional spinal kinematics. It is possible that this represents changes in whole spinal orientation and not resultant spinal motion. Despite this, SCR remains the only metric currently related to injury and therefore is important; however it is only a very modest proxy for more traditional descriptions of spinal motion.

Keywords: spine; kinematics; cricket fast bowling; inertial sensors; correlation.

Introduction

Fast bowlers in cricket have been identified as having a significantly higher risk of musculoskeletal injury compared with the rest of the team (Johnson, Ferreira, & Hush, 2012; Orchard, James & Portus, 2006). Spinal injury in the fast bowling population contributes to more than twice the number of games missed compared with any other injury (Orchard, James, Alcott, Carter & Farhart, 2002). Studies synthesising the literature have shown the prevalence of spondylolysis to be 27% for fast bowlers; significantly higher than the general and athletic populations at 6% and 12% respectively (Kalichman et al., 2009; Rossi & Dragoni, 1990). Missed playing time has been reported at 247 games over six seasons as a result of injuries to the lumbar spine (Orchard et al., 2002). Consequently, researchers have focused on attempting to identify the spinal kinematics of fast bowling and their link with spinal pathology (Johnson et al., 2012).

Previous systematic reviews have concluded that shoulder counter-rotation (SCR) in excess of 30 degrees during bowling is associated with a higher risk of developing lower back pathology, such as spondylolysis (Elliott, Davis, Khangure, Hardcastle, & Foster, 1993; Morton, Barton, Rice & Morrissey, 2013; Portus, Mason, Elliott, Pfitzner, & Done, 2004). Consequently, many previous studies have focussed on reporting SCR (Crewe, Campbell, Elliott, & Alderson, 2013; Ranson, Burnett, King, Patel, & O'Sullivan, 2008; Ranson, King, Burnett, Worthington, & Shine, 2009; Stuelcken, Ferdinands, & Sinclair, 2010). SCR is determined by subtracting the minimum shoulder alignment angle relative to the stumps, from shoulder alignment at back foot impact, as seen in figure 1 (Ranson et al., 2008). SCR values have been reported between 10-45 degrees, with mixed bowling actions typically producing higher SCR than front-on or side-on bowlers (Elliott, Hardcastle, Burnett, & Foster, 1992; Foster, John, Elliott, Ackland, & Fitch, 1989; Johnson et al., 2012). However, whilst these values may be a useful metric for coaches to quickly analyse technique, it only considers shoulder alignment. SCR does not include the pelvis as a frame of reference and therefore can be created by spinal rotation or whole body rotation or a combination of both. Therefore, the actual spinal kinematics which determine SCR are unclear and thus the mechanisms of how SCR contributes to an increased likelihood of lower back pathology remain unclear.

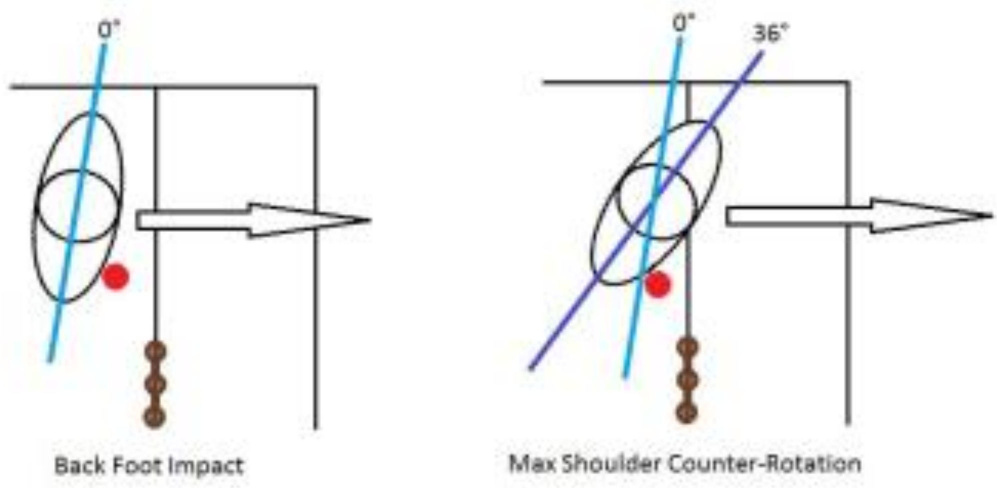

Figure 1. Calculation of shoulder counter-rotation

In addition to SCR, hip shoulder separation (HSS) angles have been used by researchers and coaches to describe bowling kinematics (Burnett, Elliott, & Marshall, 1995; Portus et al., 2004). Maximum HSS angle is typically taken between back and front foot impact and is calculated by subtracting hip orientation from shoulder orientation in the transverse plane (Burnett et al., 1995). As these values only analyse motion in a single plane they fail to describe three-dimensional spinal kinematics throughout the delivery stride.

Therefore, it remains unclear as to how SCR and HSS relate to more traditional descriptions of three-dimensional kinematics of the lumbar and thoracic spine. The aim of this study was to investigate the relationship between SCR, HSS and three-dimensional spinal kinematics during cricket fast bowling.

Method

Participants

35 elite fast bowlers from county cricket clubs participated in this study. Mean (± SD) age was 20.13 (4.62) years, height 1.84 (0.07) m and mass 80.32 (11.02) kg. Participants were excluded from the study if they reported any injury that may influence their ability to bowl maximally.

Instrumentation

Three inertial sensors (THETAmetrix, Waterlooville, UK) were attached to the skin over the T1, L1 and S1 spinous processes with double-sided tape and re-enforced with elastic adhesive bandage (As seen in figure 2). Sensors contained accelerometers, gyroscopes and magnetometers sampling at 100 Hz. An additional accelerometer (±200 g) sampling at 750 Hz was attached to the medial aspect of the mid-tibia (defined as 50% of the length of tibia) on the bowlers back leg (right leg for a right handed-bowler) with double-sided tape, vertically aligned to the tibia and secured further with a compressive bandage.

Inertial sensors have been previously validated for the analysis of spinal range of motion. Movement-time data were compared between inertial sensors and an optoelectronic system with root mean squared errors of 1.82° for flexion, and <1° for extension and lateral bending (Mjosund et al., 2017). During more rapid motions (such as sprinting), correlations of >0.99 between the inertial sensors and an optoelectronic system were observed with root mean squared error of 3^{o} (Bergamini et al., 2013). Reliability of inertial sensors has also been demonstrated during fast bowling with a mean intra-class correlation coefficient of 0.77 for lumbar, thoracic and thoracolumbar flexion, lateral flexion and rotation (Senington, Lee, & Williams, 2015).

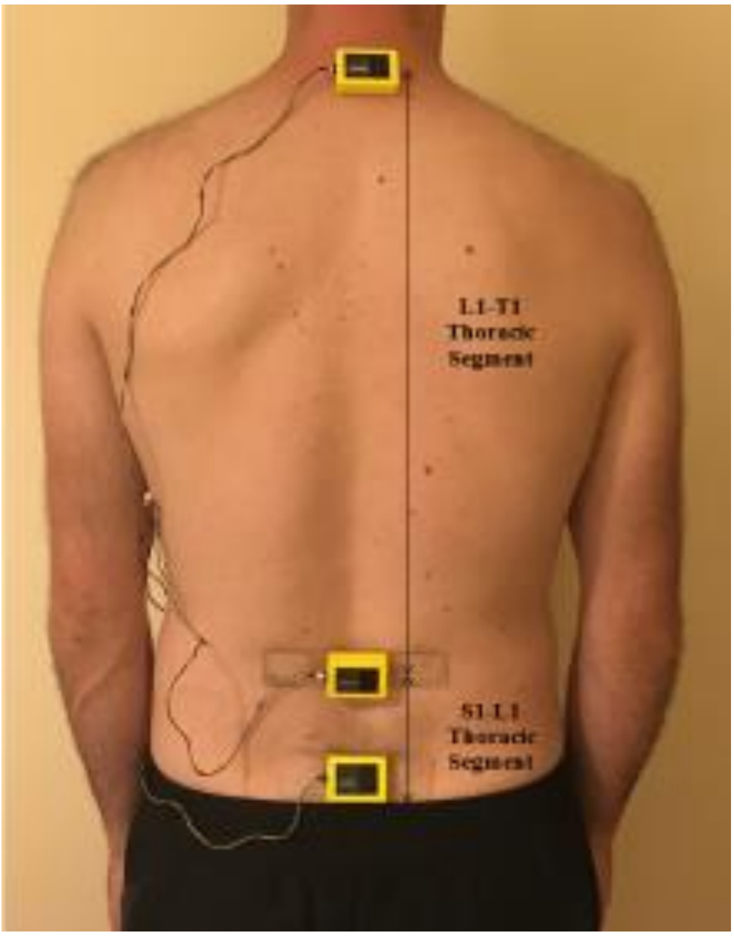

Figure 2. Placement of spinal inertial sensors

Procedure

Each bowler completed a ‘self-prescribed’ warm up until they felt ready to bowl. Bowlers were then instrumented with inertial sensors as previously described. Instructions to bowl six balls (one over) with maximal effort were given to enable the participants to familiarize themselves with bowling whilst instrumented. Following this, participants bowled with maximal effort for three balls whilst data were recorded. Instructions were given to stand stationary in their natural standing position before initiating run-up, allowing all spinal kinematics to be calculated relative to these initial angles. All bowlers bowled at a right-handed batsman in a ‘nets’ setup as part of a typical training session on grass wickets. This resulted in a total of 104 bowls being analysed due to one data collection error.

Data Processing

Inertial sensors recorded three-dimensional spinal orientation at T1, L1 and S1 and resultant angles between two sensors were computed using direction cosine matrices (Burnett, Barrett, Marshall, Elliott, & Day, 1998, Williams, Haq, & Lee, 2013) to provide angle-time data for the lumbar (S1-L1), thoracic (L1-T1) and thoracolumbar (S1-T1) segments. Extension, lateral flexion and rotation away from the direction of delivery (right lateral flexion and rotation for a right handed bowler) were negative.

Three specific points during the delivery stride were identified: back foot impact (BFI), maximum contralateral rotation of the T1 sensor (MCR) and front foot impact (FFI). The tibial accelerometer on the back leg recorded three-dimensional tibial accelerations. Peak along tibia acceleration was used to identify the BFI phase of the delivery stride. After correction for sacral tilt, peak vertical acceleration following BFI, recorded at the sacral sensor, was used to identify FFI.

Spinal range of motion from BFI to MCR and BFI to FFI were analysed. The SCR was calculated by subtracting T1 orientation at BFI from T1 orientation at MCR. The HSS was calculated as the maximum difference in hip (S1 sensor) and shoulder (T1 sensor) orientation about the longitudinal axis, as seen in figure 3 (Portus, Mason, Elliott, Pfitzner, & Done, 2004).

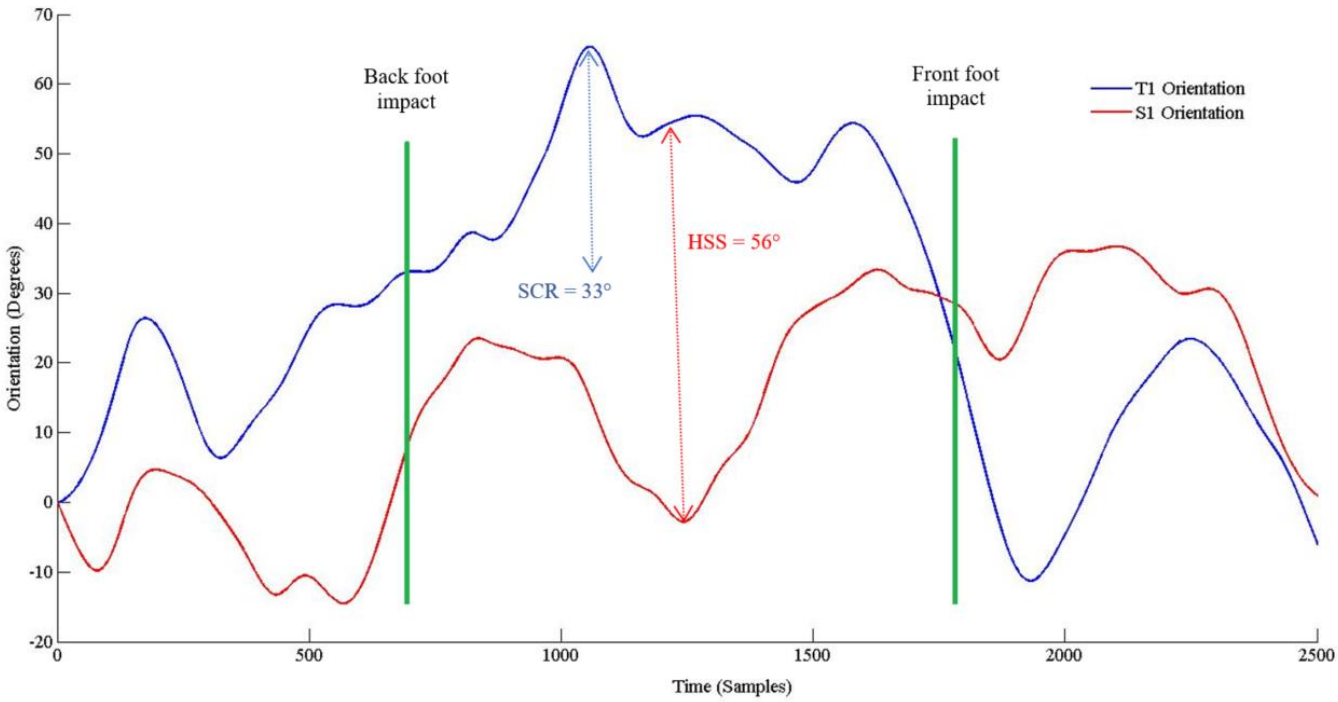

Figure 3. Orientation of the inertial sensors on the T1 and S1 vertebrae during fast bowling.

Statistical Analysis

Data were not normally distributed and despite attempting multiple transformations normality was not achieved. Therefore, a series of Spearman's pairwise correlations were performed to explore the relationship between SCR, HSS and spinal kinematics between BFI and MCR, as well as between BFI and FFI. All statistical analysis was conducted using SPSS 22 (SPSS Inc. Chicago, IL.). A Bonferroni correction for multiple significance testing was applied following initial analysis, resulting in an adjusted critical p-value of $p<0.003$.

Results

By using orientation of the hips and shoulders at BFI to classify bowling technique, as in previous studies, this study's sample consisted of 7 side-on, 19 front-on and 9 mixed action fast bowlers (Bartlett, Stockill, Elliott, & Burnett, 1996). Mean (SD) SCR and HSS values were 27.4° (±16.3°) and 33.0° (±21.6°) respectively. Maximum

SCR occurs at MCR. Whilst this is normally the same for HSS, the exact timing is technique dependent. As such, the timing of max HSS varies between bowlers.

In regards to SCR, a total of eight correlations were deemed significant (table 1). However, following Bonferroni correction for multiple significance testing, two remained significant. These significant negative correlations were observed for thoracolumbar lateral flexion and thoracic lateral flexion between back foot impact and maximum contralateral T1 rotation. This suggests if a bowler displays a greater range of thoracic and thoracolumbar lateral flexion away from the direction of delivery at the beginning of the delivery stride SCR values will be larger.

In regards to HSS angle a total of four correlations were significant (table 1), with one remaining significant following Bonferroni correction. This negative association was evident between HSS and thoracolumbar lateral flexion between back foot impact and maximum contralateral T1 rotation. This suggests that if a bowler displays greater thoracolumbar lateral flexion away from the direction of delivery at the beginning of the delivery stride, HSS angle will be larger.

Table 1. The correlation between three-dimensional spinal kinematics, shoulder counter-rotation and hip-shoulder separation values.

	Shoulder counter-rotation						**Hip-shoulder separation**			
	Back-foot impact-max contralateral T1 rotation			Back-foot impact – front-foot impact			Back-foot impact-max contralateral T1 rotation		Back-foot impact-front-foot impact	
	Mean (±SD)	r_s	*p*	Mean (±SD)	r_s	*p*	r_s	*p*	r_s	*p*
Lumbar Flexion	3.03 (15.85)	-.061	.538	35.85 (30.09)	-.141	.153	.024	.811	.031	.753
Lumbar Lateral Flexion	-20.18 (15.84)	-.254	.009	31.11 (26.06)	.095	.337	-.268	.006	.075	.450
Lumbar Rotation	-10.12 (12.88)	-.080	.421	18.12 (18.42)	-.050	.615	.077	.435	.084	.398
Thoracic Flexion	-17.49 (14.15)	-.118	.235	58.55 (32.18)	.225	.022	-.005	.956	.067	.502
Thoracic Lateral Flexion	-22.17 (18.37)	-.462	<.001*	41.43 (30.68)	.106	.285	-.255	.009	-.075	.450
Thoracic Rotation	-11.48 (9.93)	-.227	.021	29.39 (25.74)	.196	.046	-.167	.090	.075	.447
Thoracolumbar Flexion	-13.62 (12.75)	-.121	.221	80.71 (43.62)	.159	.108	-.063	.524	.020	.844
Thoracolumbar Lateral Flexion	-28.96 (21.47)	-.460	<.001*	52.46 (30.51)	.225	.022	-.552	<.001*	.041	.676
Thoracolumbar Rotation	-13.15 (11.12)	-.260	.008	39.20 (41.12)	.170	.084	-.253	.010	.008	.937

* Denotes a significant correlation following Bonferroni correction (p<.003)

Discussion

Previous research has highlighted the importance of SCR during fast bowling as this has been linked to the presence of demonstrable spinal pathology (Elliott et al., 1993; Portus, Mason, Elliott, Pfitzner, & Done, 2004). Despite this, previous research has highlighted SCR and spinal kinematics as separate variables in the analysis of performance and injury surveillance (Crewe et al., 2013; Ranson et al., 2009; Ranson et al., 2008; Stuelcken et al., 2010). However, using SCR (attained from the shoulder alignment) to explain injuries obtained in the lumbar spine is challenging as it is not clear to which three-dimensional kinematics are actually being measured.

Conversely, although analysis of three-dimensional spinal kinematics may provide a more accurate understanding of injury mechanisms, it is difficult for coaches to monitor on a regular basis. Understanding the relationship between three-dimensional spinal kinematics and measures such as SCR and HSS, that coaches can easily record and track with readily available equipment (such as video cameras) is crucial when providing recommendations to players. Only one previous study has attempted to explore the association of SCR and HSS with spinal kinematics and only lumbar kinematics were explored in relation to SCR (Crewe, Campbell, Elliott, & Alderson, 2011). Therefore, this study provides new insight into the previously explored relationship between three-dimensional lumbar kinematics and SCR, as well as novel findings relating to HSS and thoracic and thoracolumbar spinal kinematics.

Back foot impact to maximum T1 rotation

Research has highlighted that increased SCR may be used as a conscious mechanism to generate pace on the ball when bowling (Portus et al., 2004). However, as previously stated this may come at an injury cost. The results of this study illustrate that thoracic and thoracolumbar lateral flexion are the key spinal kinematic variables associated with SCR. The direction of the association is such that, bowlers with high values of lateral flexion away from the direction of delivery (right lateral flexion for the right handed bowler) are likely to display higher SCR values. It seems likely that these bowlers adopt a bowling strategy employing a wind up phase utilising spinal lateral flexion and perhaps this element is the key preparation for driving SCR and ultimately generating pace on the ball. It has been hypothesised that SCR is predominately a surrogate measure of spinal rotation (Crewe et al., 2013; Glazier, 2010) however our results show no significant correlation with spinal rotation. This may be due to the strict Bonferroni correction applied, as without this a significant correlation was identified. This suggests that SCR may be a complex interaction between lateral flexion and rotation as previously suspected (Crewe et al., 2013; Glazier, 2010).

HSS has been proposed as an additional method for coaches and researchers to describe the kinematics of fast bowling (Burnett et al., 1995; Portus et al., 2004). However, due to the need to record hip alignment, HSS is more difficult to obtain accurately using two-dimensional video analysis protocols that would be readily available to coaches. This is the first time the relationship between HSS and spinal three-dimensional kinematics has been explored. Thus, this analysis provides insight into whether presenting coaches with this additional complication is warranted. The results of this study demonstrate a significant relationship between thoracolumbar lateral flexion and HSS. The direction of the association suggests that bowlers who display greater values of lateral flexion ultimately display larger amounts of HSS. Therefore, it appears that these results mirror those for SCR.

It is important to acknowledge that despite the correlations being significant the actual magnitude was moderate ($r = .460$-$.552$, $r^2 = .212$- $.305$) suggesting a significant amount of SCR and HSS angle not explained by three dimensional kinematics as described in this study. It is therefore likely that some of these measures of SCR and HSS are produced from whole body rotations, changing whole spinal orientation, not individual spinal segment kinematics. Such movements would not contribute to a change in the resultant angle between two sensors and therefore not be recorded as resultant flexion, side flexion or rotation. The importance of which is that minimal resultant movement between vertebrae is unlikely to pose as high an injury risk as larger ranges of motion. Therefore, it is imperative to differentiate between changes in whole spinal orientation and changes in resultant spinal angles and understand what SCR and HSS are describing.

Back foot impact to front foot impact

No significant relationships were observed between SCR and HSS and spinal range of motion between back and front foot impact. This may be due to the fact that SCR describes shoulder orientation between BFI and MCR, and therefore conceptually may not be related to spinal kinematics of the whole delivery stride when movement towards the direction of delivery after MCR are considered. Furthermore, HSS does not take into account orientation relative to the wickets and is a static measure at one point in time and therefore cannot differentiate between bowling actions (a completely front-on or side-on action would both produce HSS of 0°).

Conclusion

Results of this study have highlighted that, between BFI and MCR, thoracic and thoracolumbar lateral flexion displayed significant moderate negative correlations with SCR and HSS. The direction of this association indicates larger SCR or HSS also resulted in larger lateral flexion away from the direction of delivery. Given the previously reported relationship between SCR and increased risk of lower back injury, these findings may suggest a possible mechanism of injury.

This study also reports that the use of SCR and HSS as a means of describing spinal kinematics between BFI and FFI may not be appropriate, as no significant relationships were observed between these points in the delivery stride. It may therefore be of more benefit for coaches to provide classifications of bowling action based on spinal rotation and lateral flexion. Simple in-field techniques providing real-time feedback of spinal kinematics should be sought as this will provide three-dimensional spinal kinematics and thus aid in the quest for injury reduction. However, due to its ease of measurement and reported links to lower back injury risk and performance, measurement of SCR may still be of value to coaches. Whilst HSS may be a ‘bridge’ between the more generic measure of SCR and true three-dimensional spinal kinematics; both SCR and HSS do not show a strong enough correlation to be used as surrogates for three-dimensional analysis.

Further Work

In order to more closely understand the hypothesis that; increased lateral flexion away from the direction of delivery during SCR may increase risk of injury. The analysis of the effects of an intervention to decrease initial lateral flexion on ball release speed and injury risk, would add vital insights to the current body of knowledge. Further research focussing on the development of a more representative method of technique analysis, would also aid in future monitoring of fast bowling.

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