Title Page

Title

Ground reaction force, spinal kinematics and their relationship to lower back pain and injury in cricket fast bowling. A review.

Names of Authors

Billy Senington (Corresponding author) P: 07833228335

E: billy.senington@stmarys.ac.uk

Faculty of Health and Social Sciences, Bournemouth University, Royal London House, Christchurch Road, Bournemouth, Dorset BH1 3LT, UK.

School of Health and Applied Sciences, St Mary's University, Waldegrave Road, Strawberry Hill, Twickenham, TW1 4SX.

Raymond Y. Lee

Faculty of Technology, University of Portsmouth, Portland Building, Portland Street, Portsmouth PO1 3AH, UK.

Jonathan Mark Williams

Faculty of Health and Social Sciences, Bournemouth University, Royal London House, Christchurch Road, Bournemouth, Dorset BH1 3LT, UK.

Abstract

Background: Fast bowlers display a high risk of lower back injury and pain. Studies report factors that may increase this risk, however exact mechanisms remain unclear.

Objective: To provide a contemporary analysis of literature, up to April 2016, regarding fast bowling, spinal kinematics, ground reaction force (GRF), lower back pain (LBP) and pathology.

Method: Key terms including biomechanics, bowling, spine and injury were searched within MEDLINE, Google Scholar, SPORTDiscuss, Science Citation Index, OAIster, CINAHL, Academic Search Complete, Science Direct and Scopus. Following application of inclusion criteria, 56 studies (reduced from 140) were appraised for quality and pooled for further analysis.

Results: 12 times greater risk of lumbar injury was reported in bowlers displaying excessive shoulder counter-rotation (SCR), however SCR is a surrogate measure which may not describe actual spinal movement. Little is known about LBP specifically. Weighted averages of 5.8 ± 1.3 times body weight (BW) vertically and 3.2 ± 1.1 BW horizontally were calculated for peak GRF during fast bowling. No quantitative synthesis of kinematic data was possible due to heterogeneity of reported results.

Conclusions: Fast bowling is highly injurious especially with excessive SCR. Studies adopted similar methodologies, constrained to laboratory settings. Future studies should focus on methods to determine biomechanics during live play.

Keywords: Biomechanics; cricket fast bowling; injury; lower back pain.

Introduction

Prevalence of musculoskeletal injury in the cricket fast bowling population is significantly higher than for all other players.[1,2] Observation over six seasons demonstrated that 51% of all injuries were sustained by bowlers compared to 24% for fielders, 23% for batsmen and 2% for wicket keepers.[3] Fast bowlers missed 14% of games due to injury, whilst spin bowlers only missed 4% with lower back injury resulting in the longest time absent from cricket.[3,4] Therefore it is clear that this is a population that faces great risk of injury, however injury may include demonstrable pathological change (i.e. spondylolithesis) or pain.

Epidemiological studies have suggested a relationship between cricket fast bowling and spinal pathological change.[5] The prevelance of bony abnormalities as a whole has been estimated at 24-55% in fast bowlers compared to just 6-7% in the general male population.[6-8] Spondylolysis (stress fracture of the pars) and spondylolisthesis (fracture of the pars with anterior translation of one vertebrae on another) are the most common bony pathological changes in cricket fast bolwers and junior fast bowlers at the greatest risk with estimated prevalance figures around 67%, possibly due to immature bony structures at this age.[8,9] In addition to these bony changes, a prevalence of lumbar disc degeneration at 35% has been reported in fast bowlers.[10,11] Once again adolescent fast bowlers appear at particular risk where prevalence of 44% was noted in 13 to 18 year olds.[12] In one sample of junior bowlers (16-18 years old), 23% displayed grade 1 disc degeneration; 13% grade 2 and 28% grade 3.[8] Perhaps due to the progressive nature of disc degeneration, prevelences of 70% have been observed in retired fast bowlers.[13] Therefore it is clear that fast bowlers are highly likely to display pathological change in their lumbar spine.

Despite the prevalence of pathological change it should be acknowledged that spinal abnormalities may exist without the sensation of pain, therefore low back pain (LBP) should be investigated as a separate entity.[14] LBP has been reported to result in 247 missed games in Australian domestic and international matches between 1995 and 2001.[3] Indeed almost a quarter (22.4%) of all playing time missed was attributable to LBP in fast bowlers.[3] Studies investigating LBP associated with fast bowling have reported prevalence between 40-64%.[6,8,15,16]

Previous literature has suggested that repeated exposure to high magnitudes of ground reaction force (GRF), in conjunction with combined spinal motions may be a significant factor in the pathomechanics of LBP and injury in fast bowlers.[17-19] Despite this there are no systematic reviews investigating the literature pertaining ground reaction force. Previous reviews have explored intrinsic and extrinsic risk factors for developing LBP in fast bowlers, however these reviews offer little critique of the biomechanical measurement methods used to obtain the data resulting in a faithful re-presentation of the original results.[11,20] Therefore, little insight into potential bias or flaws in methodological design was gained. The aim of this review was to critically analyse and synthesise the cricket fast bowling literature pertaining to ground reaction force and spinal kinematics during fast bowling to offer new insights into methods and conclusions relating these aspects to back pain and or pathology.

Evidence Acquisition

Search Strategy

The following electronic databases were systematically searched during April 2016; MEDLINE (1946-04/2016), Google Scholar, SPORTDiscuss (1985-04/2016), Science Citation Index (1900-04/2016), OAIster (2002-04/2016), CINAHL (1937-04/2016), Academic Search Complete (1887-04/2016), Science Direct (1872-04/2016) and Scopus (1841-04/2016). The following terms were used during the search employing Boolean search operators where appropriate; biomechanic*, kinematic*, cricket*, fast bowler*, bowl*, lumbar, back, spine, injur*, sport* injur*. Reference lists of relevant articles were also searched to identify additional literature. A PRISMA diagram illustrates the retrieval process (Figure. 1).

Inclusion Criteria

To be included in this review, articles needed to investigate spinal kinematics or GRF during cricket fast bowling. All standards of cricket were considered, as were all ages and genders. Articles had to be in the English language as no funds for translation were available. Material from magazines and editorials were excluded in order to target only peer-reviewed information. Articles reporting just the shoulder alignment were excluded as this provides no insight into spinal kinematics.

Data extraction and study appraisal

Articles were initially screened by the principal investigator using title and abstract information. Any doubt over the relevance resulted in retrieval and review of the full-text and resolution achieved through consensus with additional authors. A review of the methodological quality of the studies was completed by the principal investigator using the standardised critical review form and guidelines from Law et al. (1998) as a template.[21] This form was modified by the removal of 'intervention' due to the question of this review and nature of the studies investigated, as well as the inclusion of a mark each for sample bias, measurement bias and performance bias. This resulted in a checklist of thirteen items. Studies were separated into the main topics of GRF, spinal kinematics and injury with synthesis of results completed using odds ratios, calculated using MedCalc (V15.2) using a random effects model. Additionally, weighted averages were calculated as described in the equation below. Weighted averages enabled data pooling after consideration of sample size.

$$\text{Weighted Average GRF} = \frac{(GRF_1 \times N_1) + (GRF_2 \times N_2) + (GRF_3 \times N_3) + \ldots}{N_1 + N_2 + N_3 + \ldots}$$

Where GRF_1= Reported GRF for 'study 1' and N_1= Sample size of 'study 1'

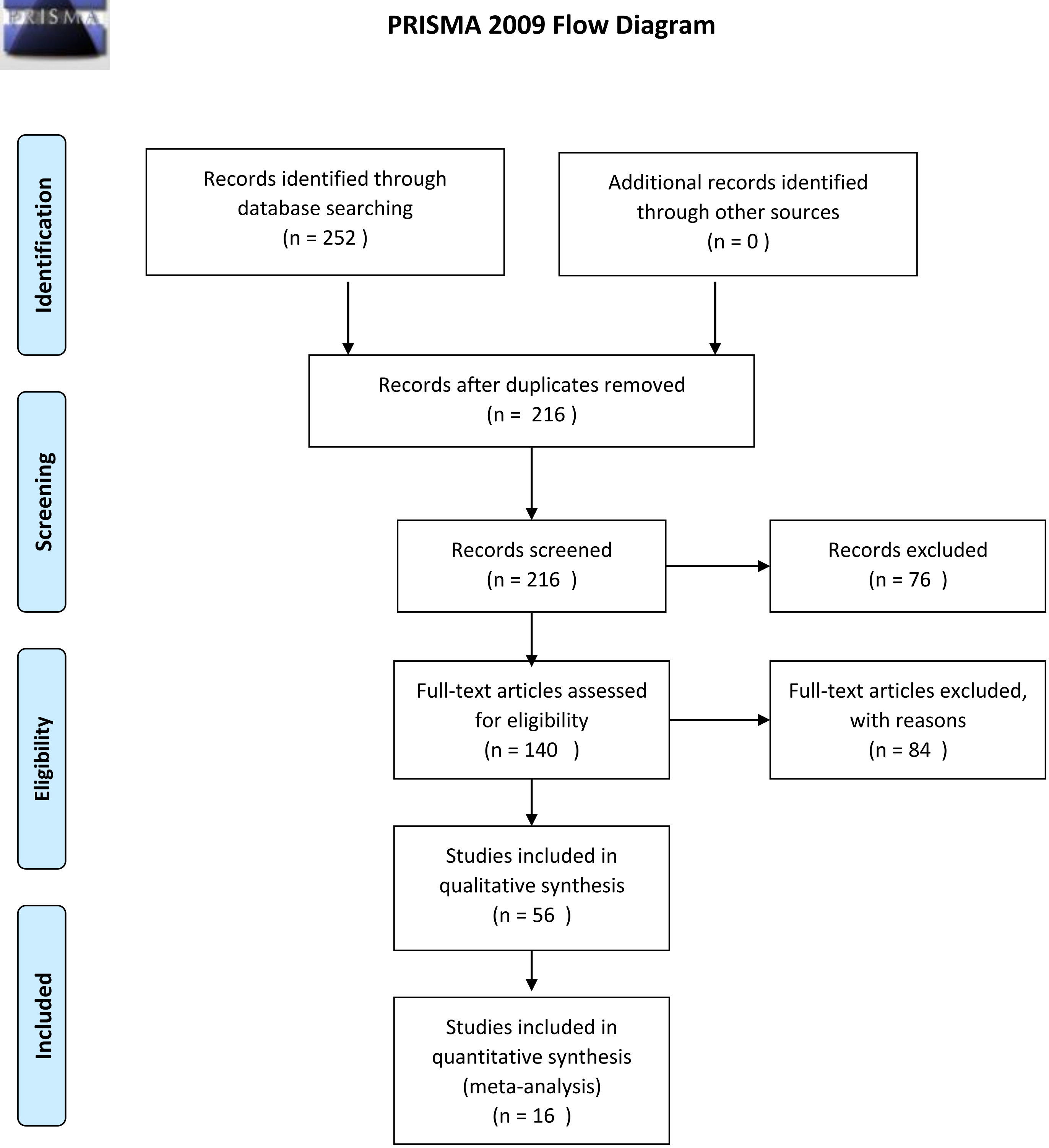

Figure 1. PRISMA flow chart of the study retrieval and screening process.

Evidence Synthesis

The systematic search resulted in 140 relevant articles which were reduced to 56 following application of the inclusion criteria. 53 articles were removed as no investigation into GRF or spinal kinematics were conducted, 15 were removed for only reporting shoulder alignments, 12 non peer-reviewed articles were removed and 4 articles not written in English. The remaining articles comprised of 16 focusing on GRF, 17 on spinal kinematics and 34 on injury. Some studies were included in more than one section.

GRF

Quality appraisal of GRF studies can be seen in table 1. Studies reporting GRF generally share common methodologies and consequently share similar threats to validity. This is evident in the repeated lack of reporting of detailed sample characteristics with inadequate description of sampling methods, making the determination of selection bias difficult. None of the studies reported a bowling history and therefore it was unclear how long individuals had been bowling or at what level. Justification of sample sizes was only reported in one study reviewed (Middleton et al. 2016). Statistical sample size calculations may offer some reassurance regarding the power of the study, however even a more pragmatic justification of sample size was missing. In light of these issues the degree to which these results are representative of the fast bowling population is unclear. Moreover, few studies have reported actual p-values making the interpretation of significance due to chance difficult. Studies also scored poorly for bias relating to testing environment. Due to the nature of the studies a typical laboratory based environment was utilised. It is possible that such an environment may affect bowling style due to physical constraints, such as run-up space, targeting the force plate or awareness of an 'unfamiliar' environment. It is not clear to what extent these factors affect GRF, however such factors could be considered limitations to the reviewed studies.

Despite previous research hypothesing a link between GRF at front foot impact and risk of LBP and injury in fast bowlers, [10,22] only one study recorded GRF and LBP.[24] However, this was in female fast bowlers so it's comparisons to the main body of fast bowling literature may be limited. Over one third of studies reported GRF alongside lower back injury data [6,22,25,26] and no results have reported a relationship between GRF and back injury.[6,22,25,27] All studies reported GRF normalised to body weight, enabling the calculation of weighted averages as a method of data synthesis. A total of 378 bowlers resulted in a weighted average (±SD) vertical GRF of 5.8 (1.3) BW and horizontal braking GRF of 3.2 (1.1) BW (table 2). Time to peak GRF was also synthesised for 82 bowlers, with a weighted average of 49 (4) ms vertically and 55 (6) ms horizontal breaking (table 3).

Table 1. Quality appraisal of fast bowling ground reaction force studies (based on Law et al. 1998)

Author	**Citation**	**Purpose**	**Literature**	**Design**	**Appropriateness of design**	**Bias: Sample Measurement Performance**	**Sample**	**Outcomes**	**Interventions**	**Results**	**Drop outs**	**Clinical implications**	**Score (/13)**
Elliott and Foster, 1984	Yes	Yes	Yes	(No) Not identified	Yes	(No) Sample: No detail on recruitment. No bowling history. (Yes) measurement (No) Performance: Lab based.	(No) No demographics. No sample size calc. No consent mentioned.	Yes	NA	(No) No statistical values reported	Yes	Yes	8
Foster and Elliott, 1985	No	(No) Not identified	Yes	(No) Not identified	(No) Not identified	(No) Sample: profile of 1 bowler. No bowling history. (No) measurement: not specified. (No) Performance: Not specified.	(No) No consent mentioned.	(No) Not described	NA	(No) No statistical values reported	Yes	Yes	3
Elliott et al. 1986	Yes	Yes	No	(No) Not identified	Yes	(No) Sample: No detail on recruitment. No bowling history. (Yes) measurement (No) Performance: Lab based.	(No) No demographics. No sample size calc. No consent mentioned.	Yes	NA	No No statistical values reported	Yes	Yes	7
Foster et al. 1989	Yes	Yes	Yes	Yes	Yes	(No) Sample: No bowling history (Yes) Measurement (No) Performance: Lab based	(No) No sample size calc. No consent mentioned.	(No) GRF, no detailed description of procedure	NA	(No) Missing p-values, or f-values.	Yes	Yes	8
Mason et al. 1989	Yes	No	Yes	(No) Not identified	Yes	(No) Sample: No bowling history. (Yes) measurement (No) performance: Lab based	(no) No demographics. No sample size calc.	Yes GRF clearly described.	NA	No actual stats presented	Yes No mention	yes	7
Elliott et al. 1992	Yes	Yes	Yes	(No) Not identified.	Yes	(No) Sample: No detail on recruitment. No bowling history. (Yes) Measurement (No) Performance: Lab based	(No) No sample size calc.	(No) Not clear	NA	(No) No actual stats presented	Yes	Yes	7
Elliott et al. 1993	Yes	Yes	Yes	(No) Not identified	Yes	(No) Sample: sample selected by coaches. No bowling history. (Yes) Measurement (No) Performance: Lab based	(No) No sample size calc.	Yes	NA	(No) No actual stats presented.	Yes	Yes	8
Hurrion et al. 2000	Yes	Yes	yes	(No) Not identified.	Yes	(No) Sample: No detail on recruitment. No bowling history. (Yes) Measurement (Yes)Performance: Outdoors (polyflex surface over Force Plate)	(No) No sample size calc.	Yes	NA	(No) No actual stats presented	Yes	(No) None mentioned.	8
Portus et al. 2004	(No)	Yes	Yes	Yes	Yes	(No)Sample: No recruitment	(No)	(No)	NA	Yes	Yes	Yes	8

	No full ref. available					detail. No bowling history. (Yes)Measurement (No)Performance: Not stated. Assumed lab based.	No sample size calc.	No detailed description of procedure					
Stuelken et al. 2009	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No recruitment detail. No bowling history. (Yes)Measurement (No)Performance: Lab based (polyflex surface over Force Plate)	(No) No sample size calc.	Yes	NA	(No) No actual stats present.	Yes	No None mentioned.	7
Crewe et al. 2013	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)Measurement: (No)Performance: Lab based.	(No) No sample size calc.	Yes	NA	(No) R and p values reported. Only as ($p<0.05$).	(No) 23 complete.	Yes	7
Worthington et al. 2013	Yes	Yes	Yes	(No) Not identified	Yes	(No)Sample: No bowling history. (Yes)Measurement (No)Performance: Lab based. (Artificial grass over Force Plate.)	(No) No sample size calc.	Yes	NA	Yes	Yes	yes	9
Spratford and Hicks, 2014	Yes	Yes	Yes	(No) Not identified	Yes	(No)Sample: No bowling history. (Yes) Measurement (No) Performance: Lab based.	(No) No sample size calc.	Yes	N/A	Yes	Yes	yes	9
Middleton et al. 2016	Yes	Yes	Yes	(No) Not identified	Yes	(No)Sample: No bowling history. (Yes) Measurement (Yes) Performance: Open Lab to allow adequate space	Yes	Yes	NA	Yes	Yes	No None mentioned	10
King et al. 2016	Yes	Yes	Yes	(No) Not identified	Yes	(No) Sample: No bowling history. (Yes) Measurement (No) Performance: Lab based.	(No) No sample size calc. No consent mentioned.	Yes	NA	Yes	Yes	Yes	9
Bayne et al. 2016	Yes	Yes	Yes	(No) Not identified	Yes	(No) Sample: No bowling history. (Yes) Measurement (No) Performance: Lab based.	(No) No sample size calc.	Yes	NA	Yes	(No) 25 complete	Yes	8

Table 2. Synthesis of results for mean vertical and breaking GRF for front-foot strike with weighted averages (SD) calculated.

Author	n	Vertical GRF (BW)	Braking GRF (BW)
Bayne et al. 2016	25	4.9	3.4
King et al. 2016	20	6.7	4.5
Middleton et al. 2016	15	3.5	2.1
	15	4.5	2.8
Spratford and Hicks, 2014	17	6.3	4.1
	17	5.9	4.0
	17	6.1	4.3
Worthington et al. 2013	20	6.7	4.5
Crewe et al. 2013	23	4.9	3.3
Portus et al. 2004	42	7.3	4.5
Hurrion et al. 2000	6	4.8	3.5
Elliott et al. 1993	19	4.8	2.1
	5	5.2	2.6
Elliott et al. 1992	20	6.4	1.9
Mason et al. 1989	15	9	2.0
Foster et al. 1989	82	5.4	2.5
Elliott et al. 1986	15	4.1	1.6
Foster and Elliott, 1985	1	3.8	1.4
Elliott and Foster, 1984	4	4.7	1.8
Weighted Average (SD)		**5.8 (1.3)**	**3.2 (1.1)**

n, number of participants; BW, body weight; GRF, ground reaction force.

Table 3. Synthesis of results for mean time to peak vertical and braking GRF for front-foot impact with weighted averages (SD) calculated.

Author	**n**	**Time to peak vertical GRF (ms)**	**Time to peak braking GRF (ms)**
Worthington et al. 2013	20	30	30
Crewe et al. 2013	23	34	37
Portus et al. 2004	9	60	70
	11	80	80
	7	80	80
	6	90	110
Hurrion et al. 2000	6	26	
Weighted Average (SD)		**49 (4)**	**55 (6)**

n, number of participants; GRF, ground reaction force; ms, milliseconds
.

Spinal Kinematics

Quality appraisal of kinematics studies can be seen in table 4. Studies measuring spinal kinematics also share common methodologies and therefore share common threats to validity. A breakdown of the actual reported spinal kinematics and methodologies used have been outlined in table 5. The sample used was inadequately described in most studies (94%). Information regarding bowling history and low back pain history was not reported. Justification of sample size was not demonstrated in any of the studies analysed. All studies, with only two exceptions, were completed in a laboratory environment.[19,28] It was common to measure GRF and kinematics simultaneously which may result in the bowler targeting the force plate, the effect of which on spinal kinematics is not known. Further limitations to laboratory based studies have been outlined above. In addition, only 47% of studies reported actual p-values or statistical test values, however this may be related specifically to the question being investigated.

It has been hypothesised that specific spinal kinematics, may contribute to increased risk of LBP and injury.[1] Although three-dimensional spinal pathomechanics are still relatively unclear; studies have identified significantly greater range of lateral flexion in injury/ LBP groups, as well as greater SCR angles.[22,25,30] However, to date there is little research correlating three-dimensional spinal kinematics with injury or LBP.[22,24,30]

Studies analysed in this review were subjected to odds ratio calculations where possible, in order to determine the effect of specific technique variables on prevalence of LBP and pathology in the fast bowling population. SCR of greater than 40° has been highlighted in research as significantly increasing risk of LBP and injury.[30] Consequently, an odds ratio [95% CI Lower, Upper] defining the chance of fast bowlers displaying SCR >40° developing LBP compared with bowlers with <40° SCR was calculated at 0.2 [0.03, 1.1]. However, an odds ratio of 11.9 [3.0, 46.9] was determined for the chance of fast bowlers displaying SCR >40° developing lower back injury.[22,30] This clearly displays the importance of separating low back injury from LBP. Recent studies have hypothesised that high range of lateral flexion may also significantly increase risk of LBP and injury, however as no clear values for excessively high lateral flexion have been reported, no groupings could be made and therefore odds ratio calculations cannot be conducted.[10,24] Any further odds ratio calculations were also made difficult by the lack of 'non-fast bowler' data available from the studies analysed, as typically only a fast bowling sample was used.

Table 4. Appraisal of quality of fast bowling spinal kinematics studies (based on Law et al. 1998)

Author	**Citation**	**Purpose**	**Literature**	**Design**	**Appropriateness of design**	**Bias:** **Sample** **Measurement** **Performance**	**Sample**	**Outcomes**	**Interventions**	**Results**	**Drop outs**	**Clinical implications**	**Score (/13)**
Foster et al. 1989	Yes	Yes	Yes	Yes	Yes	(No) Sample: No bowling history (Yes) Measurement (No) Performance: Lab based	(No) No sample size calc. No consent mentioned.	(No) GRF, no detailed description of procedure or reliability/validity	NA	(No) Missing p-values, or f-values.	Yes	Yes	8
Elliott et al. 1992	Yes	Yes	Yes	(No) Not identified.	Yes	(No) Sample: No detail on recruitment. No bowling history. (Yes) Measurement (No) Performance: Lab based	(No) No sample size calc.	(No) Not clear	NA	(No) No actual stats presented	Yes	Yes	7
Burnett *et al.* 1995	Yes	Yes	Yes	(No) Not identified	Yes	(No) Sample: No bowling history (Yes) Measurement (No)Performance: Lab based	(No) Some demographics given. No sample size calc.	Yes	NA	Yes	Yes	(No) No detailed implications	8
Burnett *et al.* 1998	Yes	Yes	Yes	(No) Not identified	Yes	(No)Sample: No bowling history. (Yes)Measurement (No) performance: Lab based	(No) No sample size calc.	Yes	NA	(No) No specific p values given	Yes	yes	8
Glazier *et al.* 2000	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history (Yes)measurement (No) performance: Lab based.	(No) No sample size calc.	Yes	NA	Yes	Yes	No	8
Portus *et al.* 2000	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)measurement (No)performance: Lab based	(No) Few demographics given. No sample size calc.	Yes	NA	Yes	Yes	No	8
Hurrion et al. 2000	Yes	Yes	yes	(No) Not identified.	Yes	(No) Sample: No detail on recruitment. No bowling history. (Yes) Measurement (Yes)Performance: Outdoors (polyflex surface over Force Plate)	(No) No sample size calc.	Yes	NA	(No) No actual stats presented	Yes	(No) None mentioned.	8
Elliot *et al. 2005*	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)Measurement (No)	(No) No sample size calc.	Yes	NA	Yes	Yes	Yes	9

						Performance: Lab based.							
Portus et al. 2004	(No) No full ref. available	Yes	Yes	Yes	Yes	(No)Sample: No recruitment detail. No bowling history. (Yes)Measurement (No)Performance: Not stated. Assumed lab based.	(No) No sample size calc.	(No) No detailed description of procedure	NA	Yes	Yes	Yes	8
Ranson *et al.* (2008)	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)Measurement (No)Performance: Lab based.	(No) No sample size calc.	Yes	NA	Yes	Yes	Yes	9
Ranson *et al. (2009)*	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)Measurement (No) Performance: Lab based.	(No) No sample size calc.	Yes	NA.	Yes	Yes	yes	9
Ferdinands *et al.* (2009)	Yes	Yes	Yes	(No) Not identified	Yes	(No)Sample: No bowling history. (Yes)Measurement (No)Performance: Lab based.	(No) No sample size calc.	Yes	NA	(No) No actual statistics reported	Yes	Yes	8
Stuelken et al. (2010)	Yes	Yes	Yes	(No) Not identified	Yes	(No)Sample: No bowling history. (Yes) Measurement (No) Performance: Lab based.	(No) No sample size calc.	Yes	NA	Yes	Yes	Yes	9
Zhang *et al.* (2011)	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: no recruitment detail. No bowling history. (Yes)Measurement (No)performance: Lab based	(No) No sample size calc.	Yes	NA	(No) No P values reported	Yes	(No) None mentioned	7
Crewe *et al. 2013b*	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)Measurement (No) performance: Lab based.	(No) No sample size calc.	Yes.	NA	(No) No R and R values reported.	Yes	yes	8
Crewe et al. 2013	Yes	Yes	Yes	(No) Not identified.	Yes	(No)Sample: No bowling history. (Yes)Measurement: (No)Performance: Lab based.	(No) No sample size calc.	Yes	NA	(No) R and p values reported. Only as ($p<0.05$).	(No) 23 completed.	Yes	7
Bayne et al. 2016	Yes	Yes	Yes	(No) Not identified	Yes	(No) Sample: No bowling history. (Yes) Measurement (No) Performance: Lab based.	(No) No sample size calc.	Yes	NA	Yes	(No) 25 complete	Yes	8

Table 5. Spinal kinematics, shoulder counter-rotation and data collection methods reported in recent fast bowling studies

Authors	Subjects (n (mean age))	Methods	Sample Frequency (Hz)	Marker/ Sensor Placement	Spinal Kinematics (° (±SD))				Shoulder Counter-Rotation (° (±SD))
					Flexion	Extension	Lateral Flexion	Rotation	
Bayne et al. 2016	12 INJ (15.5yrs) 12 NON-INJ (16yrs)	12 cam MAS & FP	250	L1, L5, left & right of L4	20.2 (3.8) 21.2 (4.7)		10.5 (3.6) 10.6 (3.4)	4.1 (1.5) 4.8 (1.6)	35.7 (12.3) 32.5 (11.8)
Crewe et al., 2013a	40 (16.2yrs)	12 cam MAS & FP.	250	ASIS, PSIS, L1, left & right of L4, L5.					35.1 (12.2)
Crewe et al., 2013b	39 (16.1yrs)	18 cam MAS & FP.	250	ASIS, PSIS, L1, left & right of L4, L5.			11 (3.3)		
Stuelcken et al., 2010	14 LBP 12 No LBP = 26 (22.5yrs)	8 cam MAS.	120	ASIS, PSIS, shoulder joint centres.	27.2 (12.1) 29.4 (10.5)	14.2 (9.1) 12.5 (8.6)	41.9 (5.8) 38.4 (6.3)	25.6 (6.1) 26.8 (5.6)	39.4 (3.2)
Ferdinands et al., 2009	21 (22.4yrs)	8 cam MAS & FP.	240	S2, T10.	38.2 (8)	5.5 (2)	15.7 (11.3)	19.4 (2.4) (Est. from %)	
Ranson et al., 2009	14 (18.5yrs)	18 cam MAS.	300	ASIS, PSIS, L1, T10.		0 (7)	34 (7)	29 (9)	45 (15)
Ranson et al., 2008	50 (23yrs)	12 cam MAS.	120	ASIS, PSIS, L1, T10.		9 (6)	34 (7)	32 (8)	41 (16)
Elliott et al., 2005	14 (<11yrs) 11 (11-13yrs) 12 (13-15yrs)	2 high speed cams.	200	PSIS, acromion processes.					23.2 21.8 Not reported.
Portus et al., 2004	42 (22.4yrs)	2 high speed cams & 2 FP.	100 & 150	Hip joint centres, shoulder joint centres.					30.75
Portus et al., 2000	14 (23.3yrs)	2 cams.	50	Acromion processes.					44 (15.8)
Glazier et al., 2000	9 (21yrs)	2 cams.	25	Unclear					28 (14)
Burnett et al., 1998	20 (19.1yrs)	ETD	120	S2, L1.	67.5	29	32.9	15.5	
Burnett et al., 1995	9 (18.1yrs)	3 high speed cams.	100	Mid ASIS-PSIS, acromion processes.					31 (16)

Cam; Camera, MAS; Motion analysis system, FP; Force plate, ETD; Electromagnetic tracking device, ASIS; Anterior Superior Iliac Spine, PSIS; Posterior Superior Iliac Spine, SD; Standard deviation

Discussion

Fast Bowling and GRF

Peak vertical GRF at front foot impact reported in fast bowling studies is considerably higher than those reported in running and jump landing (between 2-3 and 3-5 times body weight respectively).[31,32] Time to peak GRF is similar to running literature which reports time to peak around 45 ms, therefore fast bowlers may experience higher loading rates at front-foot impact compared with runners.[33] Despite this the current literature suggests that front foot impact in bowlers is either effectively attenuated up the body or remains below the injury threshold and thus appears to be unrelated to spinal injury risk. Spratford and Hicks (2014) support these conclusion, reporting increased knee flexion at higher magnitudes of GRF, in opposition to previous literature reporting higher GRF with an extended front knee.[19,34,35] However, no research has analysed the dissipation of GRF further up the body during fast bowling and thus the effects of these kinematic adjustments are unknown.

GRF Research Methodologies

Most studies employed an experimental design which included laboratory based testing. The merits of such an environment mean many confounding factors can be controlled, such as wind and weather. However, it is unclear whether bowling in such an environment accurately reflects the bowling strategies used in 'live situations.' Completing bowling inside a confined space will likely enforce constraints on run up, which can be long for fast bowlers. Furthermore, in order to land on the force plate the bowler may 'target' their front foot landing and while footfall constraints are considered a key aspect of fast bowling technique, psychological differences may still affect ecological validity and may therefore not be truly representative of 'live' bowling. Additionally, bowling in the laboratory environment is often based on the bowler aiming for specific targets, not actual stumps, the effect of this altered visual target on bowling strategy is not known.

Four studies chose to lay material over the force plate (polyflex surface and artificial grass), however no adjustments to the calculation of GRF were made.[19,23,36,37] The additional damping characteristics of the added surface are likely to have affected the actual GRF values measured. Moreover this additional material has the potential for allowing movement between the foot and force plate further affecting the values reported.

The limitations of current studies reporting GRF could be overcome by more detailed reporting of the sample used, particularly gaining greater understanding of bowling history. Bowling experience has been reported to affect the technique used as well as influence the magnitude of GRF, therefore detailed reporting of the sample used may is imperative.[28] The reporting of actual statistics values and p-values provides the reader with additional information regarding the confidence of the statistical results. All studies chose to use a force plate to measure the GRF. It is difficult to integrate such technology into live cricket testing as such a device either sits on the surface of the grass, providing a raised platform onto which the bowler must land or is sunk into the floor. This overcomes the issue with differing heights but defaces the pitch and is not portable. Moreover, the rigidity of the surface onto which the force plate sits significantly affects the GRF, requiring copious recalibration during differing conditions. In light of these limitations, a novel solution should be sought that allows for the measurement of foot kinetics in a non-defacing, simple and portable way.

Fast Bowling Kinematics

Three-dimensional spinal kinematic analyses in cricket has been reported,[24, 38-40] however, even with these more detailed measures of spinal kinematics during bowling, very few new insights into the impact of bowling technique on lower back injury and pain have resulted. SCR has repeatedly been reported as earlier studies identified it as significantly increasing risk of lower back injury, when in excess of 40°, as commonly seen in 'mixed bowling actions'.[1,22] However, the ability of SCR to describe three-dimensional spinal motion is questionable as orientation of the pelvis is not considered. The measurement represents the change in shoulder alignment relative to the wicket which could be created by spinal rotation or whole body rotation. Burnett et al. (1998) have reported a non-significant trend towards greater contralateral lumbar side-flexion with a mixed bowling action compared with other bowling actions.[41] Furthermore, contralateral side-flexion and rotation have been reported at front foot impact, placing the spine in a position of relative weakness.[22,42] However, as no values of what may be considered 'excessive' have been established and no evidence in fast bowling literature has conclusively related these variables with increased risk of injury, the precise pathokinematics remain unclear.[39,43]

Kinematic Research Methodologies

It was noted in the results section that kinematic studies shared common methodologies, however large heterogeneity existed in the actual measurement methods used. These fundamental differences prevented any data synthesis. Seven studies used a multi-camera optoelectronic motion analysis system.[18,26,38-40,44,45] Such systems allow for a wealth of kinematic information due to the freedom of multiple markers determining many body segments. Rapid sampling rates are achievable which is necessary for highly ballistic movements such as bowling. However, these methods are associated with excessive drops outs due to marker occlusion or marker loss due to sweating.[18] Furthermore, in order to use marker systems the bowler must be in a state of undress, which may not be appropriate for all cricket fast bowlers. It is noted that only one study employed different technology to video based systems, namely an electromagnetic traking device.[41] Such a device is commonplace for the measurement of three-dimensional spinal kinematics and has the distinct advantage of being portable.[46,47] Despite this, the study was still conducted in the laboratory environment. Electromagnetic tracking devices have small operating ranges due to the limited magnetic field produced, which can be overcome (as in this study) by mounting the electromagnetic source on the person.[48] However, whether wearing such a 'large sensor' (dimensions 56mm x 58mm x 56mm) interferes with the bowling technique is unclear. In addition the possibility of the wires of such a device erroneously moving a sensor has been acknowledged.[41]

When analysing lumbar kinematics, it is necessary to define a 'joint' of interest which has varied in the previous literature. Earlier studies typically measure spinal kinematics between shoulder and pelvis; thus, describing thoraco-lumbar range of motion (ROM) with the addition of shoulder girdle for studies using markers on the shoulders.[22,49,50] Other studies have demarcated the spine to just a lumbar 'joint' between S2 and L1.[41] Moreover, some studies have only reported shoulder counter-rotation, which only takes into account contralateral shoulder rotation in relation to minimum shoulder alignment without reference to the kinematics of the hips or pelvis. The absence of a pelvis frame of reference means the values may not represent actual spinal motion. Recent studies continue to report these values in favour of more traditional anatomic descriptions of ROM making comparisons to the literature outside of cricket difficult.

In order to overcome the limitations associated with laboratory constraints, line of sight difficulties and issues of magnetic field sizes, new technologies and their application to cricket fast bowling should be explored. To this end Rowlands et al. (2009) present a report on the use of inertial sensors within fast bowling practise sessions.[51] Inertial sensors have been used in the clinical analysis of 3-dimensional spinal ROM and therefore, may be able to overcome the limitations in current methods.[52]

Practical Implications

This review has highlighted the large heterogenity in reported kinematic results evident between studies, making it difficult for coaches and health practitioners to make informed decisions on any required interventions. This is also a limiting factor when trying to pool data from multiple studies, making meta-analysis difficult. SCR remains the only variable that significantly affects risk of lower back injury; however, this may be due to consistancy in reporting of this value allowing data pooling and therefore analysis of a larger sample of fast bowlers. Whilst a useful and quick measurement for coaches, SCR still fails to describe three-dimensional spinal kinematics, thus, the exact mechanism of injury is still unclear. Nonetheless, until any further guidlines can be produced coaches should continue to monitor SCR values with an aim to maintain SCR<40°.

Magnitude and time to peak GRF has shown no relationship with risk of lower back pain or injury. However, studies hypothesise that frequency of exposure to high GRF may increase risk of injury. This is in agreement with literature highlighting high bowling workloads as being associated with elevated risk. Consequently, it is advised that coaches monitor fast bowler’s training and match workloads. Fast bowlers should avoid bowling spells of greater than 10 overs to minimise risk of acute LBP, whilst bowling less than 50 overs or 2.5 days a week may decrease risk of chronic LBP and injury. Furthermore, a dramatic increase in bowling workload should be avoided.[15,30]

Further Work

To enhance future knowledge the need for detailed and accurate bowling intervention guidelines to lower the risk of LBP and spinal injury are important. In order for this to occur, limitations to previous studies should be identified and overcome. This review of the literature has attempted to highlight these limitations as a framework for researchers to design future studies in order to enhance the knowledge around cricket fast bowling and LBP and/or injury. Future studies should work towards analysis of bowling during ‘live play’ with novel minimially invasive technologies able to quantify front foot kinetics and spinal motion in a more representative manner.

Summary

This review has provided a contemporary, systematic analysis of the current literature investigating spinal kinematics and GRF during fast bowling in cricket, as well as identifying the clinical implications. Similar methodologies resulted in similar threats to validity. Spinal kinematics focussed on either shoulder-counter rotation or the anatomical planes, however studies differed in the region of the spine analysed. All kinematic studies were limited to the laboratory setting. Furthermore reporting data relating to cardinal spinal movements is recommended to aid in comparison with other literature and enable better understanding of injurious kinematics. Studies investigating the links between kinematics and LBP/injury are limited. Future research should focus on measuring GRF and kinematics of fast bowling during live cricket, overcoming the limitations outlined in this review. Linking these findings to LBP and injury is imperative to enhance the understanding of LBP and injury in fast bowling.

References

[1] Johnson M, Ferreira M, Hush J. 2012. Lumbar vertebral stress injuries in fast bowlers: A review of prevalence and risk factors. Phys Ther Sport. 2008; 13(1): 45-52.

[2] Orchard J, James T, Portus M. Injuries to elite male cricketers in Australia over a 10- year period. J Sci Med Sport. 2006; 9(6): 459-467.

[3] Orchard J, James T, Alcott E, Carter S, Farhart P. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. Brit J Sport Med. 2002; 36(4): 270-274.

[4] Stretch R. The incidence and nature of injuries in first-league and provincial cricketers. S Afr Med J. 1992; 83: 339-342.

[5] Ranson C, Kerslake R, Burnett A, Batt M, Abdi S. Magnetic resonance imaging of the lumbar spine in asymptomatic professional fast bowlers in cricket. J Bone Joint Surg Br. 2005; 87(8): 1111-1116.

[6] Elliott B, Hardcastle P, Burnett A, Foster D. The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. Res Sport Med. 1992; 3(2): 113-130.

[7] Engstrom C, Walker D. Pars interarticularis stress lesions in the lumbar spine of cricket fast bowlers. Med Sci Sport Exer. 2007; 39(1): 28-33.

[8] Hardcastle P, Annear P, Foster D, Chakera T, McCormick C, Khangure M, Burnett A. Spinal abnormalities in young fast bowlers. J Bone Joint Surg Br. 1992; 74(3): 421-425.

[9] Hardcastle P. Repair of spondylolysis in young fast bowlers. J Bone Joint Surg Br. 1993; 75(3): 398-402.

[10] Crewe H, Elliott B, Couanis G, Campbell A, Alderson J. The lumbar spine of the young cricket fast bowler: An MRI study. J Sci Med Sport. 2012; 15(3): 190-194.

[11] Morton S, Barton C, Rice S, Morrissey D. Risk factors and successful interventions for cricket-related low back pain: a systematic review. Brit J Sport Med. 2013; doi:10.1136/bjsports-2012-091782.

[12] Elliott B, Khangure M. Disk degeneration and fast bowling in cricket: an intervention study. Med Sci Sport Exer. 2002; 34(11): 1714-1718.

[13] Annear P, Chakera T, Foster D, Hardcastle P. Pars interarticularis stress and disc degeneration in cricket's potent strike force: the fast bowler. ANZ J Surg. 1992; 62(10): 768-773.

[14] Millson H, Gray J, Stretch R, Lambert M. Dissociation between back pain and bone stress reaction as measured by CT scan in young cricket fast bowlers. Brit J Sport Med. 2004; 38(5): 586-591.

[15] Dennis R, Finch C, Farhart P. Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? Brit J Sport Med. 2005; 39(11): 843-846.

[16] Kountouris A, Portus M, Cook J. Quadratus lumborum asymmetry and lumbar spine injury in cricket fast bowlers. J Sci Med Sport. 2012; 15(5): 93-397.

[17] Bartlett R, Stockill N, Elliott B, Burnett A. The biomechanics of fast bowling in men's cricket: a review. J Sport Sci. 1996; 14(5): 403-424.

[18] Crewe H, Campbell A, Elliott B, Alderson J. Lumbo-pelvic loading during fast bowling in adolescent cricketers: The influence of bowling speed and technique. J Sport Sci. 2013; 31(10): 1082-1090.

[19] Hurrion P, Dyson R, Hale T. Simultaneous measurement of back and front foot ground reaction forces during the same delivery stride of the fast-medium bowler. J Sport Sci. 2000; 18(12): 993-997.

[20] Olivier B, Taljaard T, Burger E, Brukner P, Orchard J, Gray J, Mckinon W. Which Extrinsic and Intrinsic Factors are Associated with Non-Contact Injuries in Adult Cricket Fast Bowlers?. Sport Med. 2016; 46(1): 79-101.

[21] Law M, Stewart D, Pollock N, Letts L, Bosch J, Westmorland M. Guidelines for critical review form – Quantitative studies. McMaster University Occupational Therapy Evidence-Based Practice Research Group. 1998.

[22] Portus M, Mason B, Elliott B, Pfitzner M, Done R. Cricket: Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. Sport Biomech. 2004; 3(2): 263-284.

[23] Worthington P, King M, Ranson C. The influence of cricket fast bowlers' front leg technique on peak ground reaction forces. J Sport Sci. 2012; 31(4): 434-441.

[24] Stuelcken M, Ferdinands R, Sinclair P. Three-dimensional trunk kinematics and low back pain in elite female fast bowlers. J Appl Biomech. 2010; 26(1): 52-61.

[25] Elliott B, Davis J, Khangure M, Hardcastle P, Foster D. Disc degeneration and the young fast bowler in cricket. Clin Biomech. 1993; 8(5): 227-234.

[26] Bayne H, Elliott B, Campbell A, Alderson J. Lumbar load in adolescent fast bowlers: A prospective injury study. J Sci Med Sport. 2016; 19(2): 117-122.

[27] Elliott B, Foster D, John D, Ackland T, Fitch K. Biomechanical correlates of fast bowling and back injuries in cricket. A propective study. J Biomech. 1989; 22(10): 1007.

[28] Middleton KJ, Mills PM, Elliott BC, Alderson JA. The association between lower limb biomechanics and ball release speed in cricket fast bowlers: a comparison of high-performance and amateur competitors. Sport Biomech. 2016: 15(3): 357-69.

[29] Mason B, Weissensteiner J, Spence P. Development of a model for fast bowling in cricket. Excel. 1989; 6(1): 2-12.

[30] Foster D, John D, Elliott B, Ackland T, Fitch K. Back injuries to fast bowlers in cricket: a prospective study. Brit J Sport Med. 1989; 23(3): 150-154.

[31] Bates NA, Ford KR, Myer GD, Hewett TE. Impact differences in ground reaction force and centre of mass between the first and second landing phases of a drop vertical jump and their implications for injury risk assessment. J Biomech. 2013; 46(7): 1237-1241.

[32] Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review.Clin Biomech. 2011; 26(1): 23-28.

[33] Bennell K, Crossley K, Jayarajan J, Walton E, Warden S, Kiss ZS, Wrigley T. Ground reaction forces and bone parameters in females with tibial stress fractures. Med Sci Sport Exer. 2004; 36(3): 397-404.

[34] Spratford W, Hicks A. Increased delivery stride length places greater loads on the ankle joint in elite male cricket fast bowlers. J Sport Sci. 2014; 32(12): 1101-1109.

[35] Elliott B, Foster D, Gray S. Biomechanical and physical factors influencing fast bowling. Aust J Sci Med Sport. 1986; 18(1): 16-21.

[36] Stuelcken M, Sinclair P. A pilot study of the front foot ground reaction forces in elite female fast bowlers. J Sci Med Sport. 2009; 12(2): 258-261.

[37] King MA, Worthington PJ, Ranson CA. Does maximising ball speed in cricket fast bowling necessitate higher ground reaction forces?. J Sport Sci. 2016; 34(8): 707-712.

[38] Ferdinands R, Kersting U, Marshall R. Three-dimensional lumbar segment kinetics of fast bowling in cricket. J Biomech. 2009; 42(11): 1616-1621.

[39] Ranson C, Burnett A, King M, Patel N, O'Sullivan P. The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. J Sport Sci. 2008; 26(3): 267-276.

[40] Ranson C, King M, Burnett A, Worthington P, Shine K. The effect of coaching intervention on elite fast bowling technique over a two year period. Sport Biomech. 2009; 8(4): 261-274.

[41] Burnett A, Barrett C, Marshall R, Elliott B, Day R. Three-dimensional measurement of lumbar spine kinematics for fast bowlers in cricket. Clin Biomech. 1998; 13: 574-583.

[42] Elliott B. Back injuries and the fast bowler in cricket. J Sport Sci. 2000; 18(12): 983-991.

[43] Chosa E, Totoribe K, Tajima NA. biomechanical study of lumbar spondylolysis based on a three-dimensional finite element method. J Orthopaed Res. 2004; 22(1): 158-163.

[44] Crewe H, Campbell A, Elliott B, Alderson J. Lumbo-Pelvic Biomechanics and Quadratuslumborum Asymmetry in Cricket Fast Bowlers. Med Sci Sport Exer. 2013; 45(4): 778-783.

[45] Zhang Y, Unka J, Liu G. Contributions of joint rotations to ball release speed during cricket bowling: A three-dimensional kinematic analysis. J Sport Sci. 2011; 29(12): 1293-1300.

[46] Ma HT, Griffith JF, Yang Z, Kwok AW, Leung PC, Lee RY. Kinematics of the lumbar spine in elderly subjects with decreased bone mineral density. Med Biol Eng Comput. 2009; 47(7): 783-789.

[47] Van Herp G, Rowe P, Salter P, Pual J. Three-dimensional lumbar spinal kinematics: A study of range of movement in 100 healthy subjects aged 20 to 60+ years. Rheumatology(Oxford). 2000; 39(12): 1337-1340.

[48] Milne D, Chess D, Johnson J, King G. Accuracy of an electromagnetic tracking device: A study of the optimal operating range and metal interference. J Biomech. 1996; 29: 791-793.

[49] Burnett A, Elliott B, Marshall R. The effect of a 12-over spell on fast bowling technique in cricket. J Sport Sci. 1995; 13(4): 329-341.

[50] Elliott B, Plunkett D, Alderson J. The effect of altered pitch length on performance and technique in junior fast bowlers. J Sport Sci. 2005; 23(7): 661-667.

[51] Rowlands D, James D, Thiel D. Bowler analysis in cricket using centre of mass inertial monitoring. Sport Technol. 2009; 2(1-2): 39-42.

[52] Williams J, Haq I, Lee RA. Novel approach to the clinical evaluation of differential kinematics of the lumbar spine. Manip Ther. 2013; 18(2): 130-135.

[53] Elliott B, Foster D. A biomechanical analysis of the front-on and side-on fast bowling techniques. J Hum Movement Stud. 1984; 10(2): 83-94.

[54] Foster D, Elliott B. Fast bowling: An impact sport. A profile of DK Lillee. Sports Coach. 1985; 9(3): 3-8.

[55] Glazier P, Paradisis G, Cooper S. Anthropometric and kinematic influences on release speed in men's fast-medium bowling. J Sport Sci. 2000; 18(12): 1013-1021.

[56] Portus M, Sinclair P, Burke S, Moore D, Farhart P. Cricket fast bowling performance and technique and the influence of selected physical factors during an 8-over spell. J Sport Sci. 2000; 18(12): 999-1011.