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Cricket fast bowling: The relationship between range of motion and key performance and injury technique characteristics

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ABSTRACT

Fast bowling technique characteristics associated with performance and injury have been established; however, the effect of joint range of motion (ROM) on technique remains unknown. This study aimed to investigate ROM and its effect on fast bowling technique. Eighteen ROM measures and thirteen technique parameters were determined for 45 elite male fast bowlers. Twenty-three significant correlations were found between the shoulder, hip, and ankle ROM measures and technique parameters ($r = 0.300$–0.452; $p < 0.05$). Shoulder ROM was observed to have the highest number of correlations with fast bowling technique. Increased internal rotation, less external rotation, and greater total arc of rotation were associated with technique characteristics previously linked with increased ball release speed and decreased lumbar stress injury risk. Although hip and ankle ROM were also correlated with technique, their association is yet to be understood. Future research should aim to determine the impact of ROM on fast bowling movement patterns. This knowledge is likely to be useful in enhancing the coaching and rehabilitation of fast bowlers from lumbar stress injuries.

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Ball release speed; shoulder; lumbar stress injuries; throwing

Introduction

Cricket has become world's second most participated sport and is contested between two teams containing batters and bowlers. Fast bowlers within the game attempt to deliver the ball as fast as possible towards a batter to reduce their time to interpret the delivery and play the appropriate stroke. The bowling movement consists of a run-up where linear momentum is developed which is then converted to angular momentum and transferred through the trunk and upper extremity to the ball during the bowling action (Felton et al., 2020; Worthington et al., 2013). Although dynamical systems theory indicates that individual movement patterns are determined by the process of self-organisation (Kelso, 1995) and the interaction of organismic, environmental and task constraints (Newell, 1986), the majority of research has thus far focussed on the kinematic and kinetic parameters associated with fast bowling movement patterns and their link to performance and injury rather than the effect of any constraints on fast bowling movement patterns.

A combination of technique parameters has previously been identified for fast bowling describing the optimal movement pattern for maximising ball release speed. These include faster run-up speeds, a more extended front leg, increased trunk flexion, and a longer delay in bowling arm circumduction (Felton et al., 2020; Worthington et al., 2013). Variations in movement patterns due to individual constraints have been observed, with female fast bowlers demonstrating a bowling action more reliant on developing momentum using the large rotational torso muscles rather than the run-up (Felton et al., 2019). It is likely that these movement patterns are influenced by the individual's organismic constraints, such as range of motion (ROM), but at present our understanding of how ROM affects technique characteristics linked with ball release speed in cricket fast bowling remains unknown.

Technique parameters linked to movement patterns which increase the risk of developing lumbar stress injuries have also been established (Alway et al., 2021). Within a prospective study of 50 elite fast bowlers, 88% of the 39 who developed lumbar stress injuries could be predicted within a model based on two technique characteristics: the rear leg hip angle at back foot contact (BFC) and the lumbopelvic angle at front foot contact (FFC). In addition, differences in the rear knee angle, the thoracolumbar side flexion and rotation angles, the pelvis tilt orientation, the lumbopelvic flexion angle, and the front hip angle were also observed between the injured and non-injured groups. The study concluded that lumbopelvic motion during fast bowling was key in the aetiology of lumbar stress injuries with inadequate lumbo-pelvi-femoral control, potentially due to athlete-specific strength limitations (e.g., a young developing bowler) or task-specific strength requirements (e.g., redirecting a poorly aligned centre of mass velocity at BFC). However, it has yet to be considered whether these movement patterns occur due to an individual's ROM constraints.

Few studies have investigated the relationship between ROM and technique characteristics linked to performance and injury in overhead sports such as cricket and baseball. During throwing both shoulder and hip ROM measures in cricketers and baseballers have been found to influence key performance and injury characteristics (Dutton et al., 2021; Laudner et al.,

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2015; Robb et al., 2010; Zeppieri et al., 2021). In cricket finger spin bowling, the hip ROM was associated with performance outcomes, but the shoulder ROM was not. However, this study did not investigate the impact of ROM on spin bowling kinematics (Sanders et al., 2019). One study has investigated the effect of ROM on fast bowling technique with greater performance in the active single leg raise test and shoulder horizontal abduction test linked with increased BFC-FFC duration, and FFC-BR duration, respectively (Feros et al., 2019). This study, however, was limited to these two ROM measures and a two-dimensional kinematic approach. Previous studies investigating the relationship between ROM measures and lower back and lower limb injuries in cricket fast bowling have focused on the ROMs around the lumbopelvic complex (Bayne et al., 2016; Dennis et al., 2008; Keylock et al., 2022; Stuelcken et al., 2008). Significant lumbar lateral flexion, hip internal rotation, and ankle dorsi flexion ROM differences have previously been observed when comparing between bowlers with and without a history of injury. However, these studies focus on the link between ROM and injury, rather than investigating the effect of ROM limitations on the fast bowling movement patterns.

The aim of this study therefore was to investigate ROM measures and their relationship with previously determined key performance and injury technique characteristics in elite cricket male fast bowlers.

Methods

Participants

Forty-five male fast bowlers (mean ± SD: age: 19.8 ± 2.4 years; height: 1.87 ± 0.06 m; mass: 83.7 ± 8.4 kg) participated in this study. All bowlers were identified as elite (National, A, or U19 team member, or a current professional with international potential) and were independently (National Physio) deemed fit to bowl. The testing protocol was explained to each bowler, informed consent obtained, and a pre-selection medical questionnaire completed, prior to participation in accordance with Loughborough University ethical guidelines.

Data collection

Data were captured at the ECB National Cricket Performance Centre at Loughborough University. Prior to bowling, a musculoskeletal assessment protocol (Supplementary material - Appendix A) was conducted by an experienced physiotherapist. The protocol was based on previous studies which investigated ROM in fast bowlers (Dennis et al., 2008; Keylock et al., 2022), and included: passive hip and shoulder internal and external rotations, combined shoulder elevation, passive straight leg raise, sit and reach, and ankle dorsiflexion (Supplementary Table - Appendix A). All measures have previously been shown to be highly reproducible between subjects (Bennell et al., 1998; Dacombe et al., 2011; Dennis et al., 2008; Keylock et al., 2022). In addition, ninety-five anthropometric measurements were also taken to enable subject-specific inertia parameters to be determined (Yeadon, 1990).

Once the ROM measurements were completed, each bowler had forty-seven 14 mm retro-reflective markers attached to key bony landmarks (Worthington et al., 2013). To determine the instant of ball release and ball velocity, an additional 15 × 15 mm patch of 3 M Scotch-Lite reflective tape was attached to a standard male-sized ball (weight: 0.153 to 0.160 kg). Each bowler completed a thorough self-selected warm-up and a static trial was performed to allow body segment lengths and a neutral spine position to be calculated (Ranson et al., 2008). Bowlers performed six maximal velocity deliveries of a good length (directed towards and landing 6–8 m in front of the batter's stumps) using a full-length run-up on a standard sized artificial cricket pitch with data captured using an 18 camera (MX13) Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 300 Hz.

Data processing

The fastest bowling trial with minimal marker loss was labelled using Vicon's Nexus software (OMG PLC, Oxford, UK) and imported into MATLAB (The Mathworks Inc, USA) for further processing.

The global coordinate system was defined as: x-axis – towards the bowlers right; y-axis – pointed down the wicket; and the z-axis – pointed vertically upwards. Marker trajectories were filtered at 30 Hz determined via Residual analysis (Winter, 2009). Joint centre time histories were calculated as the mid-point of two markers placed across the joint: medio-lateral for the ankle, knee, elbow, and wrist, and anterior-posterior for the shoulder. Hip joint centre time histories were determined using R. B. Davis et al. (1991) and the markers placed on the left and right anterior and posterior iliac spine. The spine joint centre time histories were determined as: lumbopelvic – the mid-point of the posterior superior iliac markers; thoracolumbar – mid-point of the xiphoid process and L1 spinous process markers; cervicothoracic – midpoint of the interclavicular notch and the C7 spinous process markers (Worthington et al., 2013). The centre of mass (COM) time history was then calculated using the joint centre time histories and subject-specific inertia data (Worthington et al., 2013).

Eighteen local three-dimensional reference frames (x-axis: medio-lateral, y-axis: anterior-posterior, z-axis: longitudinal) representing a full-body (head and neck; upper trunk; lower trunk; pelvis; 2 upper arms; 2 lower arms; 2 hands; 2 upper legs; 2 lower legs; and 2 two-segment feet) were determined using the marker trajectories (Worthington et al., 2013). Segmental orientation time histories and joint angles were calculated as Cardan angles using an xyz sequence. Segment orientation rotations corresponded to tilt about the x-axis, drop about the y-axis, and twist about the z-axis. Similarly, joint angle rotations corresponded to flexion-extension about the x-axis; abduction-adduction about the y-axis; and longitudinal rotation about the z-axis. Orientations and joint angles correspond to the anatomical position and the bowling side (anatomical position = 180°; anterior tilt or flexion, contralateral drop or side flexion, and contralateral twist or rotation<180°; Figure 1). All joint angles reported refer to flexion-extension unless otherwise stated.

The bowler's BFC and FFC were identified manually as the first frame in which the motion of the respective foot changed due to contact with the ground (Worthington et al., 2013). Ball

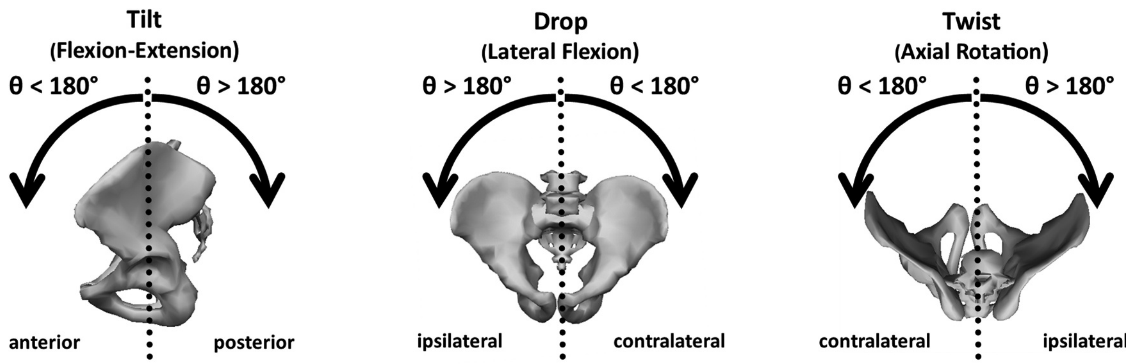

Figure 1. Segment orientation (and joint angle) local reference frames for a right handed bowler. For a left-handed bowler, the contralateral and ipsilateral directions reverse for drop (lateral flexion) and twist (axial rotation).

release (BR) was determined as the frame when the rate of change of the distance between the wrist joint centre and the ball was greater than 20 mm between frames (Worthington et al., 2013). Ball release velocity was calculated over a period of 10 frames post-BR using the equations of constant acceleration (Worthington et al., 2013). Run-up velocity was calculated as the mean horizontal (global y-axis) mass centre velocity over a period of 18 frames pre-BFC (Worthington et al., 2013).

Statistical analysis

Thirteen technique parameters and eighteen ROM measures were put forward for analysis. The technique parameters included six previously linked with performance (Worthington et al., 2013): ball release speed, run-up speed, front knee angle at BR, thoracic flexion between FFC and BR, and bowling shoulder angle at FFC and BR; and seven previously linked with lumbar stress injuries (Alway et al., 2021): rear knee angle at BFC, rear hip angle at BFC, front hip angle at FFC, thoracolumbar side flexion at BFC and BR, thoracolumbar rotation at BFC, pelvic tilt at FFC, and lumbopelvic angle at FFC. The ROM measures included 16 unilateral measurements (eight for the dominant side and eight for the non-dominant side): passive internal, external, and total arc of rotation (internal and external ROM combined) of the shoulder and hip, passive straight leg raise, and ankle dorsi flexion (knee to wall); and two bilateral ROM measurements: combined shoulder elevation and sit and reach.

Statistical analyses were performed using SPSS (Version 28.0, IBM, USA). Normality of the data was confirmed via Shapiro–Wilk tests and the assumption of equal variances by Levene's tests. Associations between technique parameters and ROM measures were investigated using Pearson product moment correlation analyses. Alpha values of 0.05 were used to determine significance No adjustment was made for multiple comparisons due to the previously reported risk of increasing Type-2 errors (Sinclair et al., 2013).

Results

The 45 bowlers in this study produced ball release speeds in the range 32.0–39.8 m/s (Table 1). Descriptive statistics of the key performance and injury technique characteristics and ROM measures are presented in Tables 1 and 2.

Ball release speed was not found to be correlated with any of the ROM measures (Table 3). Ten significant correlations were found between the ROM measures and the key technique parameters previously linked with ball release speed (Table 3). Greater front knee angles at BR were correlated with decreased non-dominant (front) hip internal rotation ($r = -0.452$, $p = 0.002$) and total arc of rotation ($r = -0.303$, $p = 0.043$), as well as decreased non-dominant (front) shoulder

Table 1. Range, mean, and standard deviation for the key performance and injury-related technique characteristics.

technique parameter	range	mean ± S.D.
performance		
ball release speed (m/s)	32.0–39.8	35.7 ± 1.6
run-up speed (m/s)	5.31–7.10	6.14 ± 0.52
front knee angle at BR (°)	121.0–190.4	163.5 ± 20.9
thoracic flexion FFC to BR (°)	16.2–48.5	30.3 ± 7.5
bowling shoulder angle at FFC (°)	301.2–376.1	341.8 ± 18.5
bowling shoulder angle at BR (°)	182.2–253.5	220.1 ± 16.5
injury		
rear knee angle at BFC (°)	107.2–172.3	145.6 ± 14.2
rear hip angle at BFC (°)	122.7–169.6	145.9 ± 11.1
front hip angle at FFC (°)	115.8–154.9	130.0 ± 8.4
pelvic tilt at FFC (°)	160.1–182.6	170.0 ± 4.4
lumbopelvic angle at FFC (°)	169.8–190.7	177.0 ± 5.4
thoracolumbar side flexion at BFC (°)	167.4–196.1	181.8 ± 6.0
thoracolumbar side flexion at BR (°)	148.0–172.2	163.2 ± 4.7
thoracolumbar rotation at BFC (°)	166.0–187.4	177.9 ± 4.7

Table 2. Range, mean and standard deviation of the ROM measures.

	dominant		non-dominant	
measure	range	mean ± S.D.	range	mean ± S.D.
combined				
shoulder elevation (cm)	7–43	22 ± 8		
sit and reach (cm)	2–38	21 ± 10		
shoulder	*bowling arm*		*non-bowling arm*	
internal rotation (°)	41–105	62 ± 10	57–90	75 ± 8
external rotation (°)	105–146	125 ± 11	96–132	114 ± 10
total arc of rotation (°)	147–207	187 ± 12	168–209	188 ± 10
hip	*rear leg*		*front leg*	
straight leg raise (cm)	59–117	77 ± 11	58–114	77 ± 10
internal rotation (°)	20–46	32 ± 8	18–55	32 ± 8
external rotation (°)	34–68	48 ± 8	25–70	48 ± 8
total arc of rotation (°)	59–95	79 ± 10	55–100	79 ± 9
ankle	*rear leg*		*front leg*	
dorsi flexion (mm)	30–200	109 ± 36	10–185	103 ± 32

external rotation ($r = -0.316$, $p = 0.037$). Greater bowling shoulder angles at BR were associated with increased dominant (bowling) shoulder internal rotation ($r = 0.351$, $p = 0.018$). While greater thoracic flexion between FFC and BR was linked with increased dominant and non-dominant shoulder total arc of rotation (dominant: $r = 0.327$, $p = 0.028$; non-dominant: $r = 0.417$, $p = 0.005$), non-dominant (front) shoulder external rotation ($r = 0.370$, $p = 0.014$), non-dominant (front) hip internal rotation ($r = 0.427$, $p = 0.003$) and total arc of rotation ($r = 0.429$, $p = 0.003$), and dominant (rear) hip internal rotation (0.317, $p = 0.034$).

Thirteen significant correlations were also observed between the ROM measures and the key injury-related technique parameters (Table 4). Greater rear hip angles at BFC were correlated with increased dominant (bowling) shoulder external rotation ($r = 0.378$, $p = 0.010$) and total arc of rotation ($r = 0.320$, $p = 0.032$). Greater front hip angles at FFC were associated with decreased non-dominant (front) shoulder external rotation ($r = -0.307$, $p = 0.043$), as well as decreased non-dominant (front) hip internal rotation ($r = -0.387$, $p = 0.009$) and total arc of rotation ($r = -0.307$, $p = 0.040$). Non-dominant (front) shoulder rotations were also correlated with three other technique parameters: greater thoracolumbar rotation at BFC was linked with increased internal rotation ($r = 0.310$, $p = 0.038$), greater thoracolumbar side flexion at BFC was associated with decreased internal rotation ($r = -0.424$, $p = 0.004$) and total arc of rotation ($r = -0.317$, $p = 0.036$), and greater lumbopelvic angles at FFC were related with decreased internal rotation ($r = -0.301$, $p = 0.044$) but increased external rotation ($r = 0.309$, $p = 0.041$). Greater pelvic tilt at FFC was correlated with decreased non-dominant (front) hip internal rotation ($r = -0.299$, $p = 0.046$), and greater thoracolumbar side flexion at

Table 3. Pearson correlation coefficients between ROM measures and key performance-related technique characteristics.

	ball release speed	run-up speed	front knee angle at BR	thoracic flexion FFC to BR	bowling shoulder angle at FFC	bowling shoulder angle at BR
combined						
shoulder elevation	−0.110	−0.005	−0.114	0.284	−0.021	0.114
sit and reach	0.066	0.240	0.132	0.096	0.257	0.001
dominant shoulder (bowling arm)						
internal rotation	0.106	0.005	0.110	0.110	−0.112	***0.351****
external rotation	−0.058	0.102	0.010	0.266	−0.156	−0.054
total arc of rotation	0.032	0.096	0.097	***0.327****	−0.230	0.232
non-dominant shoulder (front arm)						
internal rotation	0.085	0.027	0.145	0.035	−0.050	0.283
external rotation	−0.182	0.196	***−0.316****	***0.370****	−0.150	−0.183
total arc of rotation	−0.111	0.267	−0.183	***0.417****	−0.208	0.061
dominant hip (rear leg)						
straight leg raise	0.051	0.167	0.183	0.115	0.210	−0.052
internal rotation (°)	−0.152	−0.193	*-0.228*	**0.317***	0.024	−0.063
external rotation (°)	0.186	−0.097	0.067	0.074	0.000	0.171
total arc of rotation (°)	0.035	−0.219	−0.114	0.292	0.018	0.089
non-dominant hip (front leg)						
single leg raise	−0.007	0.158	0.104	0.124	0.093	−0.044
internal rotation (°)	−0.247	0.092	**−0.452***	**0.427***	−0.073	−0.021
external rotation (°)	0.184	0.030	0.115	0.057	−0.088	0.066
total arc of rotation (°)	−0.061	0.108	**−0.303***	**0.429****	−0.140	0.039
dominant ankle (rear leg)						
dorsi flexion	−0.061	0.020	−0.027	0.288	−0.109	0.046
non-dominant ankle (front leg)						
dorsi flexion	0.011	0.018	0.051	0.197	−0.008	0.047

*Significant correlation at the 0.05 level.

Table 4. Pearson correlation coefficients between ROM measures and key injury-related technique characteristics.

	rear knee angle BFC	rear hip angle BFC	front hip angle FFC	thoracolumbar side flexion BFC	thoracolumbar rotation BFC	pelvic tilt FFC	lumbopelvic angle FFC	thoracolumbar side flexion BR
combined								
shoulder elevation	0.159	−0.047	−0.206	−0.050	0.022	−0.172	0.151	0.150
sit and reach	0.022	0.166	−0.059	0.120	−0.098	−0.069	0.165	0.026
dominant shoulder (bowling arm)								
internal rotation	0.105	−0.025	−0.053	−0.169	0.229	−0.022	−0.164	0.003
external rotation	0.225	**0.378***	−0.105	0.003	−0.005	−0.041	0.157	−0.017
total arc of rotation	0.286	**0.320***	−0.137	−0.132	0.178	−0.054	0.011	−0.013
non-dominant shoulder (front arm)								
internal rotation	0.166	0.144	0.140	**−0.424***	**0.310***	0.075	**−0.301***	0.118
external rotation	−0.036	0.027	*−0.307**	0.056	−0.126	−0.143	**0.309***	−0.174
total arc of rotation	0.073	0.153	−0.185	*−0.317**	0.147	−0.070	0.061	−0.065
dominant hip (rear leg)								
single leg raise	0.032	0.168	−0.170	0.161	−0.194	−0.146	0.115	−0.079
internal rotation (°)	−0.055	0.059	*-0.188*	0.180	−0.266	−0.195	0.097	0.090
external rotation (°)	−0.076	−0.166	−0.011	−0.093	0.105	0.016	0.047	−0.135
total arc of rotation (°)	−0.101	−0.087	−0.147	0.058	−0.112	−0.131	0.109	−0.041
non-dominant hip (front leg)								
single leg raise	0.010	0.129	−0.250	0.140	−0.165	−0.193	0.150	−0.073
internal rotation (°)	−0.080	−0.169	**−0.387***	−0.044	−0.030	**−0.299***	0.101	0.003
external rotation (°)	0.177	0.148	0.043	0.016	−0.011	0.057	0.121	−0.092
total arc of rotation (°)	0.082	−0.022	**-0.307***	−0.025	−0.035	−0.217	0.194	−0.077
dominant ankle (rear leg)								
dorsi flexion	0.028	0.078	−0.058	−0.006	−0.022	−0.206	0.205	**−0.343***
non-dominant ankle (front leg)								
dorsi flexion	−0.007	−0.070	0.002	0.059	−0.088	−0.054	0.097	**−0.301***

*Significant correlation at the 0.05 level.

BR was associated with decreased ankle dorsi flexion of both legs (dominant: $r = -0.343$, $p = 0.021$; non-dominant: $r = -0.301$, $p = 0.045$).

Discussion

This study aimed to investigate ROM constraints in elite cricket fast bowlers and their relationships with key performance and injury technique characteristics. Although no significant relationships were found between the ROM measures and ball release speed, hip and shoulder internal rotation, external rotation, and total arc of rotation, as well as ankle dorsiflexion were all found to be associated with key performance (Table 3) or injury technique characteristics (Table 4). These results indicate that fast bowling technique may be limited by ROM constraints.

The role of the bowling arm in cricket fast bowling technique is well established with increased ball release speeds associated with delayed arm circumduction (Felton et al., 2020; Tyson, 1976; Worthington et al., 2013). The bowlers in this study with greater dominant shoulder internal rotation had more delayed bowling shoulder angles at BR (Table 3). The amount of trunk flexion between FFC and BR has also been heavily implicated to generate higher ball release speed (Burden & Bartlett, 1990; Elliott et al., 1986; Felton et al., 2020; K. H.Davis & Blanksby, 1976; Portus et al., 2004; Worthington et al., 2013). It has been suggested that delayed bowling arm circumduction helps to increase ball release speed by facilitating more trunk flexion to occur, whilst still allowing the arm to deliver the ball towards the intended target at ball release (Felton et al., 2020). In this study, the bowlers with increased trunk flexion exhibited greater shoulder total arcs of rotation in both the dominant and non-dominant sides (Table 3). These findings indicate that fast bowling technique may be affected by dominant (bowling) shoulder ROM constraints which limits individual bowler's delaying the bowling arm and increasing trunk flexion.

Straighter rear leg kinematics at BFC have been linked with significantly reducing the odds of prospective lumbar stress injuries in elite cricket fast bowlers (Alway et al., 2021). Dominant (bowling) shoulder external rotation and total arc of rotation were the only ROM measures associated with rear hip angles at BFC (Table 4). Straighter rear hip kinematics were associated with increased ROM of both measures. It has been discussed that bowlers who exhibit flexed rear leg kinematics at BFC adopt this position due to the necessity to produce the increased torque available at the mid-range of the joint (Thorstensson et al., 1976) to redirect the centre of mass velocity (Alway et al., 2021). Although athlete-specific strength limitations at straighter joint angles (e.g., a young developing bowler) and task-specific strength requirements (e.g., redirecting a poorly aligned centre of mass velocity at BFC) have been proposed as potential causes (Alway et al., 2021), the findings within this study may provide an additional explanation. Athlete-specific shoulder ROM constraints may cause bowlers to adopt potentially injurious movement strategies in the bowling action to ensure the bowling arm is orientated to deliver the ball towards the target at ball release.

The three non-dominant (front) shoulder ROM measures (internal, external, and total arc of rotation) combined had the highest number of significant associations with the key performance and injury technique characteristics (Table 4). Bowlers with smaller internal rotation had more contralateral thoracolumbar rotation, more ipsilateral side flexion at BFC, and more lumbopelvic extension at FFC. A smaller total arc of rotation was also associated with more ipsilateral side flexion at BFC. In addition, bowlers with greater external rotation had more front knee and hip flexion at FFC, and more lumbopelvic extension at FFC. These correlations align with technique characteristics reported in bowlers who experienced prospective lumbar stress injuries (Alway et al., 2021). This potentially implicates decreased internal rotation, increased external rotation, and decreased total arc of rotation of the shoulders in the aetiology of lumbar stress injuries.

The impact of shoulder ROM on fast bowling technique appears substantial based on the findings of this study (Tables 3 and 4). The non-dominant shoulder ROM likely provides a good representation of the bowling shoulder prior to its adaptation, and potentially during the learning phase of the movement. The ROM requirements linked with non-injurious kinematics conflict with previously observed bilateral shoulder adaptations in fast bowlers – a gain in external rotation and a loss of internal rotation in the bowling shoulder in relation to the non-bowling shoulder (Sundaram et al., 2012). These previously observed adaptations at the shoulder are consistent with those observed in throwers (Sauers et al., 2014). Although unknown, it is possible that throwing may be counterproductive to developing and maintaining a safe fast bowling technique due to conflicting movement patterns and ROM adaptations. Future research should focus on understanding the effect of shoulder ROM on fast bowling kinematics and investigate the cause and effect of bilateral shoulder adaptation in cricket bowlers.

Bowlers with greater non-dominant (front) internal hip rotation exhibited more hip flexion and less pelvic tilt at FFC, and more knee flexion at BR (Tables 3 and 4). Similar findings were found for the non-dominant (front) hip total arc of rotation with more front hip flexion at FFC and more knee flexion at BR (Tables 3 and 4). Although an explanation for these findings is not obvious, they provide evidence that hip rotation ROM may influence technique characteristics previously linked with ball release speed (Worthington et al., 2013) and lumbar stress injury (Alway et al., 2021). Whilst these causal relationships may exist, studies investigating the relationship between hip rotation ROM and injury occurrence have found conflicting results (Bayne et al., 2016; Dennis et al., 2008; Keylock et al., 2022). In addition, previous research has indicated that bowlers with less linear momentum at BFC may adopt a rotational technique more akin to throwing which utilises the large rotational muscles to rotate the pelvis and torso segments (Felton et al., 2019). Greater internal rotation and total arc of rotation of the non-dominant (front) hip may allow increased rotation of the pelvis about the front leg. A similar link between non-dominant (front) hip internal and total arc of rotation and spin rate has been observed in elite finger spin bowlers (Sanders et al., 2019). Dominant and non-dominant hip internal rotation, and non-dominant (front) hip total arc of rotation were also correlated with trunk flexion between FFC and BR. More research is required however to understand how the kinematics and kinetics of the fast bowling action are influenced by the ROM of the hips.

Greater ankle dorsi flexion ROM was linked to increased contralateral thoracolumbar side flexion at BR. Lateral trunk flexion is contributed to by both thoracolumbar side flexion and lumbopelvic side flexion. Previous findings have highlighted bowlers who remain lumbar stress injury free have greater ankle dorsi flexion (Dennis et al., 2008), and generate lateral trunk flexion using greater amounts of thoracolumbar side flexion rather than lumbopelvic side flexion (Alway et al., 2021). Although unclear, it is possible that greater ankle dorsiflexion ROM is required to orientate the pelvis appropriately during the bowling action. Ankle dorsi flexion ROM limitations may result in increased knee and hip flexion at back foot contact, which have previously been associated with increased lumbar side flexion and lumbar stress injuries (Alway et al., 2021). Although increased lumbopelvic side flexion has been associated with the destabilisation of the pelvis within the fast bowling action, it is unclear how ankle dorsi flexion may limit fast bowling technique and potentially destabilise the pelvis. The focus of further investigation should be to understand this relationship between ankle dorsi flexion and fast bowling technique.

A major strength of this research is the large number of elite fast bowlers which participated in the biomechanical analysis and the ROM screening. Although there is still potential for a sample size bias since the population consisted solely of males from one nation, and ROM is variable between genders and ethnicities. Another potential limitation concerns investigating ROM measures versus previously identified discrete performance and injury technique characteristics rather than investigating these within the current cohort. In addition, ROM measures are intra-variable on a number of factors including the time of day, previous activity, and level of warm-up. Since it was decided to allow bowlers to follow their own self-selected warm-ups as they would do normally, an attempt to control the effect of the level of warm-up on the ROM measures was made by testing ROM pre-warm up. The disadvantage of allowing self-selected warm-ups is that some players may achieve a greater increase in ROM after warming up than others. Finally, the findings should be considered cautiously as multiple correlations were made without an adjustment to the alpha level to reduce the risk of Type 2 errors occurring (Sinclair et al., 2013).

Conclusion

This study is the first to investigate ROM measures for elite male fast bowlers and their relationships with key performance and injury technique characteristics. Bilateral shoulder ROM differences were observed with more external rotation ROM and less internal rotation ROM in the dominant (bowling) side. No difference was observed in the total arc of rotation of the shoulders, potentially suggesting that this is a protective shift in ROM. Shoulder ROM was observed to have the largest number of correlations with the key performance and injury technique characteristics. Greater internal rotation, decreased external rotation, and increased total arc of rotation were associated with technique characteristics linked with increased ball release speed and reduced lumbar stress injury risk. The conflicting findings between the bilateral adaptation observed and the effect of shoulder ROM measures on fast bowling kinematics may indicate the adaptation is due to another skill (e.g., throwing). Further links between hip rotation and dorsi flexion ROM were identified but require further research to understand how these constraints affect the kinematics of the fast bowling action. The results of this research are likely to be useful in enhancing the coaching and rehabilitation of fast bowlers from lumbar stress and other injuries. Coaches and sports practitioners should consider the effect reduced shoulder ROM has on fast bowling kinematics and incorporate this knowledge within their practice. Future research should focus on understanding the effect of shoulder ROM on fast bowling kinematics and investigate the cause of bilateral shoulder adaptation in cricket bowlers.

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Appendix A

The musculoskeletal protocol performed prior to bowling for each fast bowler and the associated intra-class correlation coefficient (ICC) previously reported for each test.

Test name	Test measures	Test procedure	ICC	Equipment used
Passive shoulder internal rotation	Shoulder ROM	Participant lies crooked, with the shoulder abducted to 90 degrees, elbow flexed to 90 degrees and the forearm in mid-prone. The tester passively moves the shoulder to the end of internal rotation and the angle is recorded on the posterior aspect of the forearm just distal to the wrist joint.	0.73[a]	A standard physiotherapy table, and a digital inclinometer (model: MDP01, Tacklife – Aukey E-Business Co. Ltd., Shenzhen, China)
Passive shoulder external rotation	Shoulder ROM	Participant lies crooked, with the shoulder abducted to 90 degrees, elbow flexed to 90 degrees and the forearm in mid-prone. The tester passively moves the shoulder to the end of external rotation and the angle is recorded on the anterior aspect of the forearm just distal to the wrist joint.	0.92[a]	A standard physiotherapy table, and a digital inclinometer (model: MDP01, Tacklife – Aukey E-Business Co. Ltd., Shenzhen, China)
Combined shoulder elevation	Shoulder ROM	Participant lies prone with both arms overhead with elbows extended and hands interlocked. Participant is asked to lift their hands off the ground as high as possible whilst maintaining elbow extension and forehead contact with the ground. The distance (cm) between the ulna styloid and the ground is recorded.	0.97[b]	A 1 metre rigid ruler.
Passive hip internal rotation	Hip ROM	Participants lies prone with knees together and flexed to 90 degrees. The feet fall to the side whilst knees stay together and angle is recorded from the medial aspect of the tibia, just medial to the tibial plateau.	0.94[c]	A standard physiotherapy table, and a digital inclinometer (model: MDP01, Tacklife – Aukey E-Business Co. Ltd., Shenzhen, China)
Passive hip external rotation	Hip ROM	Participant lies supine with knees just off the table with contralateral foot resting on table. The tester passively moves the hip to the end of external rotation and the angle is recorded on the lateral aspect of the leg, just superior to the lateral malleolus.	0.96[c]	A standard physiotherapy table, and a digital inclinometer (model: MDP01, Tacklife – Aukey E-Business Co. Ltd., Shenzhen, China)
Passive straight leg raise	Hamstring flexibility	Participant lies supine whilst the tester supports the heel, holding the foot in plantar grade, whilst flexing the hip and making sure the knee is held in extension. The tester uses their thigh closest to the plinth to stabilise the contralateral hip into extension. The tester flexes the hip until a firm end feel is reached and records the range of hip flexion just distal to the tibial tubercle.	0.97[c]	A standard physiotherapy table, and a digital inclinometer (model: MDP01, Tacklife – Aukey E-Business Co. Ltd., Shenzhen, China)
Sit and reach	Hamstring and lower back flexibility	Participant sits with legs long and straight with feet against the sit and reach box. They smoothly move their hands forward, pushing the marker on the sit and reach box as far as possible whilst keeping both hands together. The tester monitors the knees to make sure they are held in extension. 3 trials are conducted. The maximum distance the fingertips reach on the box is recorded.	0.97[c]	A standard sit and reach box
Ankle dorsiflexion (knee to wall)	Ankle ROM	The participant stands with their hips, shoulders, and feet parallel to the wall with their toes touching the wall. The participant brings their knee to the wall whilst keeping their foot flat on the floor. The foot is moved further and further away from the wall until the heel begins to lift or the knee no longer touches the wall. The distance (cm) between the wall and the big toe is recorded.	0.97–0.98[d]	A 30 cm ruler taped to the floor.

Note: In all tests, if the subject reported pain, the ROM was recorded at the onset of pain.

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