Medicine and Science in Sports and Exercise

Lumbar Bone Mineral Adaptation:
The Effect of Fast Bowling Technique in Adolescent Cricketers

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Abstract

Introduction: Localised bone mineral density (BMD) adaptation of the lumbar spine, particularly on the contralateral side to the bowling arm, has been observed in elite male cricket fast bowlers. No study has investigated this in adolescents, or the role of fast bowling technique on lumbar BMD adaptation. This study aims to investigate lumbar BMD adaptation in adolescent cricket fast bowlers, and its relationship with fast bowling technique. **Methods:** 39 adolescent fast bowlers underwent antero-posterior DXA scan of their lumbar spine. Hip, lumbopelvic and thoracolumbar joint kinematics, and vertical ground reaction kinetics were determined using 3D motion capture and force plates. Significant partial (covariate: fat free mass) and bivariate correlations of the technique parameters with whole lumbar (L1-L4) BMD and BMD asymmetry (L3 and L4) were advanced as candidate variables for multiple stepwise linear regression. **Results:** Adolescent fast bowlers demonstrated high lumbar Z-Scores (+1.0; 95%CI: 0.7 – 1.4) and significantly greater BMD on the contralateral side of L3 (9.0%; 95%CI: 5.8 – 12.1%) and L4 (8.2%; 95%CI: 4.9 – 11.5%). Maximum contralateral thoracolumbar rotation and maximum ipsilateral lumbopelvic rotation in the period between back foot contact (BFC) and ball release (BR), as well as contralateral pelvic drop at front foot contact (FFC), were identified as predictors of L1-L4 BMD, explaining 65% of the variation. Maximum ipsilateral lumbopelvic rotation between BFC and BR, as well as ipsilateral lumbopelvic rotation and contralateral thoracolumbar side flexion at BR, were predictors of lumbar asymmetry within L3 and L4. **Conclusion:** Thoracolumbar and lumbopelvic motion are implicated in the aetiology of the unique lumbar bone adaptation observed in fast bowlers whereas vertical ground reaction force, independent of body mass, was not. This may further implicate the osteogenic potential of torsional rather than impact loading in exercise-induced adaptation.

Keywords: osteogenic adaptation, internal loading, physical activity, lumbar spine, biomechanics

Introduction

Bone is a dynamic tissue which adapts to exercise loading by responding to internal strains via bone re/modelling (1). This is necessary to ensure mechanical competence and reduce risk of fragility or overuse fracture (1), and conforms with the previous suggestions that increases in human bone formation are associated with bone strain (2). It has been suggested that the adaptation of bone is caused by strains derived mainly from muscular forces (3,4), and/or from ground reaction forces (4,5). This has been demonstrated in athletes who participate in activities with high vertical impacts such as gymnastics and basketball (6–8), or high muscular forces such as tennis and baseball (9,10), who have marked osteogenic adaptation. Adaptations are often site-specific, localised at the specific skeletal sites experiencing the greatest strain (11,12). Increases in bone mineral density (BMD) have been observed in the legs of soccer players (13), the calcaneus and lumbar spine of volleyball and basketball players (14), and the humerus of tennis players (15). Asymmetric adaptations have also been observed between the arms of baseball pitchers (9) and tennis players (10), with significantly greater bone mass and bone strength indices in the dominant arm compared to the non-dominant arm. Research using 3D scanning methodologies has demonstrated that adaptations are much more localised, for instance with differences across the proximal femur in sports with different loading patterns (11,12), including greater cortical thickness in highly loaded sites.

Cricket is the second most popular sport in the world and is a bat and ball game played by two teams of eleven on a large field. The fielding team, including bowlers who either deliver fast or spinning balls across a 20.12 m pitch, aim to prevent the batting side scoring runs by dismissing them or limiting runs scored. The laws of cricket state that the ball must be delivered overarm and must not be thrown. Consequently, fast bowlers employ a technique in which they run up towards the pitch (elite male mean ± SD: 5.79 ± 0.58 m/s, (16)) before bounding into the delivery phase in which there are high vertical ground reaction forces (6.72 ± 1.42 bodyweights (17); VGRF) and multiplanar trunk movements at front foot contact. At this time, high forces have been estimated at the lumbar spine, (vertical force: 4.89 ± 0.88 bodyweights; lateral force: 0.42 ± 0.13 bodyweights; anterior force -1.37 ± 0.69 bodyweights (18)), while finally, the extended bowling arm rapidly accelerates towards the target before releasing the ball (Supplementary file 1). Fast bowlers deliver the ball at velocities often in excess of 40 m/s (16) in an attempt to reduce the reaction time in which batters can interpret the path of the ball, and have annual match workloads in excess of 2000 balls (19). Previous research using 2D-based dual x-ray absorptiometry (DXA) has demonstrated that elite male fast bowlers have high lumbar (L1-L4) BMD (BMD: 1.56 ± 0.16 g/cm^2; Z-score: 2.45 ± 1.24), particularly on the contralateral side of the lumbar spine (opposite to the bowling arm), which increases inferiorly, peaking at L4, where BMD is 14.6% greater than on the ipsilateral side (20). This asymmetric presentation of the lumbar spine is likely in response to the asymmetric fast bowling technique, which may put greater strain within the contralateral side of the lumbar spine, in relation to the bowling arm. It is unknown whether this asymmetric adaptation is caused by the large vertical ground reactions experienced during front (contralateral) foot contact, or from the muscle induced forces associated with multi-planar trunk movement.

At present, there is no knowledge of the adaptation of the lumbar spine in adolescent fast bowlers, where peak VGRF's are often lower (6.7 BW in adults (17) v 4.8 BW in adolescents (21)) due to body size and muscle mass, and where vertebral size is likely less, as well as reduced repetition due to workload management directives (22).

Lumbar bone stress injuries (LBSI) are the most prevalent injury in cricket and occur mostly in fast bowlers, on the contralateral side to the bowling arm (23). Although the relationship between BMD and fast bowling technique has not been investigated, literature has focussed on investigating the aspects of fast bowling technique which characterise bowlers who have experienced LBSI with those that have not (24–26). Recent research has implicated the motion of the lumbopelvic joint in the aetiology of LBSI in cricket fast bowlers (27). Although localised low BMD could contribute to LBSI risk in fast bowlers (20), there is little understanding of the effect of fast bowling technique on the bone adaptation in the contralateral side of the lumbar spine in cricket fast bowlers.

An understanding of the aetiology of lumbar bone mineral adaptation in cricket fast bowlers is important because of the high prevalence of LBSI in this population (23). This aim of this study is twofold: (1) to investigate whether bone mineral adaptation of the lumbar spine exists in adolescent cricket fast bowlers; (2) to investigate the kinematic and kinetic characteristics of fast bowling technique which are linked with bone adaptation in cricket fast bowlers.

Methods

Participants

Thirty-nine adolescent male fast bowlers identified as ‘fast’ if the wicket keeper would normally stand back from the stumps (27), were recruited from professional academies or schools and clubs with well-developed cricket programmes. Participants were included if they were aged 14-17 with at least two years’ experience of high-level cricket. Participants were excluded if they had any disease or used medications which affect bone health, any condition that may contraindicate X-ray exposure, known current LBSI, or unusual pathological changes or metal implants in the lumbar spine. Subjects with history of LBSI were not excluded and bowling workload variables were not included in analysis due to the difficulty in accurately assessing them prior to inclusion. Ethical approval for the study was obtained and approved by both: the Loughborough University Ethics Approvals (Human Participants) Sub-Committee (LUEASC) and the National Research Ethics Service (NRES). Written informed consent was obtained prior to study inclusion or parental consent for those under the age of 16 years, and a health questionnaire completed to ensure each bowler was fit to bowl by identifying any active injuries that prevented individuals from bowling at 100%.

Data collection

All participants bowled a minimum of 12 maximal effort deliveries targeting a 'good length' – landing 4-7 m from the batter's stumps (28). Each delivery was recorded using an 18-camera Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 300 Hz, which was synchronised with two Kistler force plates, sampling at 1800 Hz and located to capture front foot GRF data (Type 9287CA, Winterthur, Switzerland). Data were collected within an indoor biomechanics laboratory incorporating a full-length artificial cricket pitch with space for a full run-up. Forty-seven retro-reflective markers (14 mm diameter) were attached to the participants over bony landmarks in accordance with the marker set previously described by Worthington et al. (16). Additionally, a 2 cm^2 piece of reflective tape was placed on the ball to allow the instant of ball release and release speed to be determined. To allow body segment lengths and neutral spine positions to be calculated, static and dynamic calibration trials were also performed by each bowler prior to bowling (29).

DXA

Each participant received a total body and anteroposterior lumbar spine (L1-L4) DXA scan (GE Lunar iDXA, GE Healthcare, USA) on the same day as bowling data collection. Participants laid supine with legs raised as the lower legs rested on a block of appropriate height to reduce lumbar lordosis. BMD and Z-scores were derived for L1-L4 using standard analysis (Lunar enCore v17, GE Healthcare, USA). BMD was also calculated for the lateral third of the contralateral and ipsilateral sides of the vertebrae of L3 (CL3, IL3) and L4 (CL4, IL4) using a custom analysis which omits the spinous process (20), as L3 and L4 demonstrated the greatest asymmetry in elite male fast bowlers (20). Total body scans were used to determine fat free mass (FFM). Precision error (%CV) the measured lumbar spine BMD values were: L1-L4 (0.4%), IL3 (2.4%), CL3 (1.8%), IL4 (2.3%), CL4 (1.9%) (20).

Data processing

Kinematic and kinetic parameters describing fast bowling technique were calculated from the trial with the greatest ball release speed, minimal marker loss, and where the front foot landed on the force plate. This trial was manually labelled and processed using Vicon's Nexus software (OMG Plc, Oxford, UK). Marker trajectories were filtered using a recursive fourth-order low-pass Butterworth filter with a cut-off frequency of 30 Hz determined using Winter's residual analysis (30). Back foot contact (BFC) was manually identified as the first frame in which displacement of a foot marker on the back foot was altered due to interaction with the ground, and front foot contact (FFC) was identified as the first frame in which VGRF exceeded 25 N (16). Ball release (BR) was determined as the frame in which the distance between the ball marker and the mid-point of a pair of markers over the wrist exceeded 20 mm relative to the previous frame (16).

The ankle, knee, shoulder, elbow and wrist joint centres were calculated from the pair of markers placed medio-lateral across each joint (anterior-posterior for the shoulder) so the midpoint coincided with the joint centre (16). The hip joint centres were calculated from left and right anterior and posterior superior iliac spine markers (31). The lumbopelvic junction was defined by the mid-point of the left and right posterior superior iliac spine markers, the thoracolumbar junction was defined as the mid-point of the markers placed on the xiphoid process and L1 spinous process, and the mid-point of the interclavicular notch and the C7 spinous process defined the cervicothoracic junction (16).

The global coordinate system was defined with the y-axis pointed down the wicket in the direction of forward movement, the x-axis towards the bowler's right, and the z-axis pointing vertically upwards. Similarly, local three-dimensional reference frames where the y-axis pointed forwards, the x-axis pointed towards the bowlers right, and the z-axis pointed upwards along the longitudinal axis of the segment, were determined for 18 segments (head and neck; upper trunk; lower trunk; pelvis; 2 x upper arm; 2 x lower arm; 2 x hand; 2 x upper leg; 2 x lower leg and 2 x 2-segment feet) using three markers on each segment (16). Global segment orientation and joint angles were calculated as Cardan angles using an *xyz* sequence (27). The global orientation angles corresponded to: x - tilt, y -drop and z – twist; with orientations described relative to the bowling side (anterior tilt, contralateral drop and twist <180°). The joint angle rotations corresponded to: x -flexion-extension, y - abduction-adduction, and z - longitudinal rotation; (16), with angles described relative to the anatomical position and bowling side (anatomical position = 180 degrees: flexion, contralateral side flexion and rotation <180 degrees). All angles reported within the results correspond to the flexion-extension axis unless otherwise stated. Ball release speed was calculated over a period of 10 frames (0.033 s) from the instant of BR using the equations of constant acceleration (16).

Peak forces, average loading rates and impulse in the vertical and horizontal direction were determined (16). Average loading rates were calculated as the peak force divided by the time from initial foot contact to the time of peak force (27). Peak forces, average loading rates and impulses were explored in absolute and normalised terms (using the bowlers' body mass), as it is unknown whether absolute or relative ground reaction force is a contributor to BMD.

Forty-seven kinematic parameters which have musculature that interacts with the lumbar spine (hip angle at BFC; front hip angle at FFC; thoracolumbar and lumbopelvic extension, side flexion and rotation at BFC, FFC, BR and the minimum and maximum values between BFC and BR; and pelvis orientation tilt, drop and twist, at BFC, FFC and BR, and the minimum and maximum values between BFC and BR) and 6 kinetic parameters (peak force, average loading rates and impulse in the vertical direction in both absolute and body mass normalised terms) were determined for statistical analysis.

Statistical Analysis

All statistical analyses were performed within SPSS v.26 (SPSS Corporation, USA). Side to side differences between the contralateral and ipsilateral side of L3 and L4 were determined by calculating mean percent ([contralateral – ipsilateral] / ipsilateral x 100) differences and their 95% confidence intervals (CI). 95% CIs not crossing zero were considered statistically significant as determined by a single sample t-test with a population mean of 0% (32).

To identify the technique parameters associated with lumbar bone adaptation, two approaches were used: (1) the relationship between fast bowling technique parameters and whole lumbar (L1-L4) BMD was investigated; (2) the relationship between fast bowling technique parameters and the asymmetry in BMD across L3 and L4 was investigated.

To investigate the effect of fast bowling technique on lumbar bone adaptation, partial correlations were calculated between each kinematic and kinetic parameter with L1-L4 BMD. Pearson product moment correlations were calculated between each kinematic and kinetic parameter and L3 and L4 asymmetry. As FFM has been positively associated with lumbar BMD (33) and peak VGRF (initial analysis: $r = 0.673$, $p < 0.001$), FFM was used as a covariate for calculations including L1-L4 BMD and VGRF. An alpha value of 0.05 was used to determine significance. To determine the effect of fast bowling kinematics and kinetics on the magnitude of asymmetry at L3 and L4, Pearson product momentum correlations were determined for each of the kinematic and kinetic parameters.

To identify the key technique predictors of the lumbar bone mineral measures, the parameters which were significantly correlated ($p < 0.05$) with either whole lumbar BMD or BMD asymmetry across L3 and L4 were put forward as 'candidate' variables for input into a forward stepwise linear regression model for each of the lumbar bone mineral measures. The regression model for whole lumbar BMD was hierarchical with fat free mass entered prior to the forward stepwise regression. The entry requirement for the inclusion of a parameter into the regression equation was $p < 0.05$, with a removal coefficient of $p > 0.10$. The regression model was also rejected if the coefficient 95% confidence intervals included zero, the residuals of the predictor were heteroscedastic or if the bivariate correlations, tolerance statistics or variance inflation factors showed any evidence of multicollinearity (34). The normality of the standardised residuals was also confirmed via a Shapiro-Wilk test. The percentage of variance of the dependent variables (bone mineral measures) explained by the independent (kinematic and kinetic) variables in each regression equation was determined by Wherry's (35) R^2-value. This represents an attempt to estimate the proportion of variance that would be explained by the model had it been derived from the population (adolescent male fast bowlers) from which the sample was taken. To overcome the potential limitations of stepwise regressions relying on a single best model, the explained variance for all possible regression equations with the same number of predictor variables as the stepwise solution was determined for comparison.

Results

The 39 participants (mean ± SD; age: 15.6 ± 1.1 years; height: 1.79 ± 0.07 m; mass: 68.7 ± 10.7 kg; fat free mass: 56.5 ± 8.3 kg) produced ball speeds in the range: 23.1 – 35.1 m/s (mean ± SD: 28.89 ± 2.98 m/s) and demonstrated mean (SD) L1-L4 BMD and Z-Score of 1.214 ± 0.199 g/cm^2 and +1.0 ± 1.2 (95%CI: 0.7 – 1.4) respectively. In addition, the participants exhibited contralateral to ipsilateral BMD asymmetry of 9.0 ± 9.6% (95%CI: 5.8 – 12.1%) at L3; and 8.2% ± 10.1 % (95%CI: 4.9 – 11.5%) at L4 which was significantly different to 0% ($p < 0.001$).

Four of the 47 kinematic and kinetic parameters (Table 1 and Supplementary File 2) were found to be linearly correlated with whole lumbar BMD when the effect of FFM was controlled for ($p < 0.05$; Table 2). A further five parameters were observed to be linearly correlated with lumbar BMD asymmetry across L3 and L4 ($p < 0.05$; Table 2). These nine variables were investigated initially for multicollinearity using bivariate correlations. The thoracolumbar rotation angle at BFC was found to be significantly correlated with both the maximum contralateral thoracolumbar rotation angle between BFC and BR, and thoracolumbar side flexion at BFC, with a Pearson's correlation coefficient greater than 0.75, so it was removed as a 'candidate' variable (34). Similarly, the lumbopelvic rotation angle at FFC was also removed as a candidate variable due to a Pearson's correlation coefficient greater than 0.75 with the maximum ipsilateral lumbopelvic rotation angle between BFC and BR. All other correlations were below the 0.75 threshold and were entered into the forward stepwise linear regression.

Table 1 – Mean ± SD of kinematic and kinetic parameters of adolescent fast bowlers.

parameters	**BFC**	**FFC**	**BR**	**Min (BFC to BR)**	**Max (BFC to BR)**
kinematic					
back hip angle (°)	151 ± 9				
front hip angle (°)		134 ± 10			
pelvis orientation – tilt (°)	188 ± 7	171 ± 6	155 ± 10	153 ± 9	190 ± 7
pelvis orientation – drop (°)	191 ± 7	177 ± 5	166 ± 7	165 ± 6	193 ± 6
pelvis orientation – twist (°)	233 ± 13	221 ± 12	166 ± 13	166 ± 13	246 ± 14
lumbopelvic angle (°)	168 ± 6	176 ± 5	162 ± 7	161 ± 6	178 ± 5
lumbopelvic angle – side flexion (°)	179 ± 5	167 ± 7	172 ± 4	161 ± 5	181 ± 5
lumbopelvic angle – rotation (°)	171 ± 8	203 ± 9	187 ± 6	169 ± 8	207 ± 10
thoracolumbar angle (°)	178 ± 11	180 ± 9	157 ± 11	157 ± 11	187 ± 9
thoracolumbar angle – side flexion (°)	183 ± 5	187 ± 8	160 ± 4	157 ± 5	190 ± 7
thoracolumbar angle - rotation (°)	178 ± 4	178 ± 5	194 ± 6	174 ± 4	200 ± 7
kinetic – front foot					
peak vertical GRF (kN)					3.5 ± 1.2
peak vertical GRF (BW)					5.2 ± 1.3
vertical loading rate (kN/s)					131 ± 90
vertical loading rate (BW/s)					199 ± 142
vertical impulse (N.s)					85 ± 48
vertical impulse (BW.s)					0.12 ± 0.06

The best individual technique predictor of L1-L4 BMD (with FFM controlled for), was the maximum contralateral thoracolumbar rotation angle between BFC and BR which explained 56.7% of the variance (Table 3; Figure 1). Greater thoracolumbar contralateral rotation within the bowling action between BFC and BR characterised bowlers with higher L1-L4 BMD. Adding maximum ipsilateral lumbopelvic rotation angle into the regression equation increased the variance explained to 61.5%, with the bowlers with higher L1-L4 BMD demonstrating less lumbopelvic ipsilateral rotation between BFC and BR (Table 3; Figure 1). The regression equation was improved further, explaining 65.2% of the variance, by including pelvic drop at FFC, with greater contralateral drop characterising higher L1-L4 BMD (Table 3; Figure 1). No other combination of candidate variables with significant p-values which could explain the variance in L1-L4 BMD were found, including investigating removed alternative candidate variables due to multicollinearity.

Table 2 – Significant partial (covariate: fat free mass) and bivariate correlations between lumbar bone mineral measures and the kinematic and kinetic fast bowling parameters.

		confidence intervals		
parameters	*r*	lower bound	upper bound	*P*
Partial correlations (covariate: fat free mass)				
L1-L4 BMD				
maximum pelvis orientation (BFC -BR) - twist (°)	0.331	0.027	0.604	0.042
thoracolumbar angle at BFC - side flexion (°)	0.325	0.037	0.595	0.046
thoracolumbar angle at BFC - rotation (°)	-0.430	-0.668	-0.107	0.007
minimum thoracolumbar angle (BFC to BR) - rotation (°)	-0.452	-0.670	-0.166	0.004
Bivariate correlations				
L3 BMD % difference				
pelvis orientation at FFC - drop (°)	-0.342	-0.647	0.044	0.033
lumbopelvic angle at FFC – rotation (°)	0.411	0.168	0.640	0.009
maximum lumbopelvic angle (BFC to BR) - rotation (°)	0.365	0.108	0.590	0.022
L4 BMD % difference				
lumbopelvic angle at BR – rotation (°)	0.460	0.188	0.663	0.003
thoracolumbar angle at BR - side flexion (°)	0.390	0.056	0.696	0.014

Abbreviations: back foot contact (BFC); front foot contact (FFC); ball release (BR).

Table 3 – Forward stepwise linear regression models for bone mineral measures (p < 0.05)

			95% Confidence interval			
model	**parameters**	**coefficient**	***lower bound***	***upper bound***	**p**	**percentage explained**
a) L1-L4 BMD						
1	fat free mass (kg)	0.017	0.011	0.023	<0.001	47.1%
	constant	0.265	-0.065	0.595	0.112	
2	fat free mass (kg)	0.014	0.008	0.019	<0.001	56.7%
	minimum thoracolumbar rotation angle (°)	-0.016	-0.026	-0.005	0.004	
	constant	3.170	1.209	5.131	0.002	
2	fat free mass (kg)	0.015	0.010	0.021	<0.001	61.5%
	minimum thoracolumbar rotation angle (°)	-0.018	-0.028	-0.008	0.001	
	maximum lumbopelvic rotation angle (°)	-0.005	-0.010	-0.001	0.025	
	constant	4.614	2.378	6.851	<0.001	
3	fat free mass (kg)	0.018	0.012	0.024	<0.001	65.2%
	minimum thoracolumbar rotation angle (°)	-0.020	-0.030	-0.011	<0.001	
	maximum lumbopelvic rotation angle (°)	-0.008	-0.013	-0.003	0.003	
	pelvis orientation at FFC - drop (°)	-0.010	-0.018	-0.001	0.037	
	constant	7.044	3.933	10.156	<0.001	
b) L3 %						
1)	maximum lumbopelvic rotation angle (°)	0.368	0.055	0.680	0.022	11.0%
	constant	-67.10	-131.8	-2.445	0.042	
2)	maximum lumbopelvic rotation angle (°)	0.457	0.162	0.753	0.003	24.6%
	thoracolumbar angle at BR - side flexion (°)	0.886	0.238	1.534	0.009	
	constant	-227.709	-359.4	-95.98	0.001	
c) L4 %	lumbopelvic angle at BR – rotation (°)	0.802	0.286	1.318	0.003	19.0%
	constant	-141.6	-238.0	-45.19	0.005	

Abbreviations: front foot contact (FFC); ball release (BR).

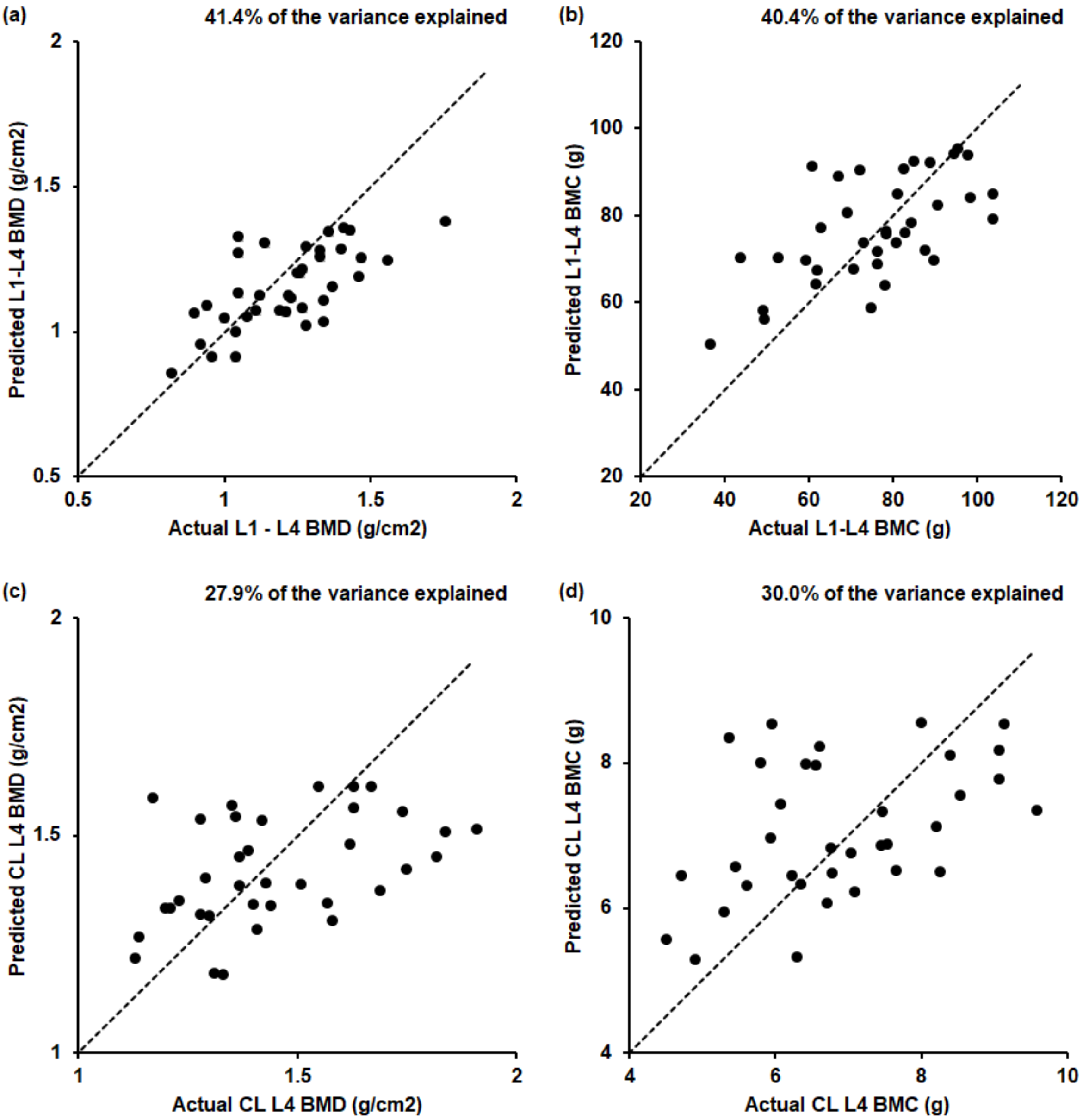

Figure 1 – Predicted versus observed lumbar bone mineral for the four stepwise two-parameter regression models (a-d; Table 2). With a higher percentage of the variation in the lumbar bone mineral measure the closer the data points lie to the dashed line y = x (predicted = actual).

The best individual technique predictor of BMD asymmetry was the motion of the lumbopelvic rotation joint during the fast bowling action (Table 3). Higher asymmetry in BMD across L3 was characterised by larger maximum ipsilateral rotation angles, with 14.7% of the variation explained. A more ipsilaterally rotated lumbopelvic rotation angle at BR was associated with greater asymmetry in BMD across L4, explaining 19.0%. Adding the thoracolumbar side flexion angle at BR to the model predicting the asymmetry in BMD across L3 increased variance explained to 22.7%, with less thoracolumbar contralateral side flexion associated with greater asymmetry. When investigating removing the alternative candidate variables it was found that greater ipsilateral lumbopelvic rotation at FFC was a better individual predictor than the maximum rotation between BFC and BR, explaining 14.7% of the variance in L3 BMD asymmetry. When thoracolumbar side flexion was added however, the model was only capable of explaining 22.7% of the variance compared to 24.6% in the model using lumbopelvic rotation at FFC. No other combination of candidate variables with significant p-values which could explain the variance in L3 or L4 adaptation were found.

Discussion

This study is the first to consider lumbar bone adaptation in adolescent cricket fast bowlers. The mean lumbar (L1-L4) Z-Score (+1.0; 95%CI: 0.7 – 1.4) of the adolescent fast bowlers was high, suggesting that fast bowling has a significant positive osteogenic impact. In addition, adolescent fast bowlers also demonstrated significantly greater BMD on the contralateral side of L3 and L4 (9.0% and 8.2% respectively). Lumbar BMD was lower in adolescent fast bowlers compared with what we previously reported in elite fast bowlers (1.21 ± 0.20 g/cm^2 v 1.56 ± 0.16 g/cm^2, independent t-test: $p < 0.001$), and had a similar asymmetric adaptation at L3 (9.0% v 8.9%, independent t-test: $p = 0.972$), but with a smaller asymmetric magnitude at L4 compared with elite fast bowlers (8.2% v 14.6%, independent t-test: $p < 0.001$) (20). This may be explained by age related (bone maturation, bone geometry, body size, muscle mass and historic workload) increases in BMD (36).

The single best technique predictor of lumbar BMD was the maximum contralateral thoracolumbar rotation angle between BFC and BR, which explained 56.7% of the variation once FFM had been accounted for (Table 3; Figure 1). The bowlers with the highest BMD had larger maximum contralateral rotation of the thoracic spine relative to the lumbar spine. The importance of the motion of the thoracolumbar rotation angle with lumbar BMD during the fast bowling action is highlighted by the significant relationship (Pearson's correlation coefficient>0.80; p<0.05) between the maximum contralateral thoracolumbar rotation angle between BFC and BR, and the thoracolumbar rotation angle at BFC. The maximum ipsilateral thoracolumbar rotation angle, and the thoracolumbar rotation angle at FFC and BR, were not predictors of lumbar BMD. This highlights that the thoracolumbar rotation which is correlated with lumbar BMD occurs prior to FFC.

The rotation of the lumbopelvic joint was the best predictor of BMD asymmetry across L3 and L4, as well as the second best predictor of whole lumbar BMD (Table 3; Figure 1). The bowlers with the greatest asymmetry in BMD across L3 had larger maximum ipsilateral rotation angles between BFC and BR (Table 3), while larger lumbopelvic ipsilateral rotation angles at BR were associated with greater asymmetry in BMD across L4 (Table 3). Since the maximum lumbopelvic rotation angle between BFC and BR was heavily correlated with the lumbopelvic rotation angle at FFC, this suggests that the rotation of the lumbopelvic joint commencing close to the timing of FFC and continuing through to BR is most likely to be associated with the adaptation in BMD across L3 and L4. While a greater maximum lumbopelvic ipsilateral rotation angle between FFC and BR was associated with larger asymmetry in BMD across L3 and L4, a smaller maximum lumbopelvic ipsilateral rotation angle between BFC and BR was associated with increased whole lumbar BMD within the regression equation (Table 3). A possible reason for these seemingly conflicting associations, is that larger lumbopelvic ipsilateral rotations translate the load further towards the contralateral side and inferior vertebrae (L3-L4), resulting in the asymmetric adaptations observed in this study and previously in elite male cricket fast bowlers (20). While smaller lumbopelvic ipsilateral rotations likely maintain more of the strain across the whole lumbar region (L1-L4), and this increases BMD in this region.

The association of thoracolumbar and lumbopelvic rotations with lumbar bone mineral measures potentially highlights torsional loading as the aetiological mechanism. Previous research has indicated that torsional loading places the greatest strain upon bone compared with other loading directions (37). This is evidenced by the large adaptations observed in the playing humerus of tennis and baseball players (9,10), both of which produce large torsional loads. It is believed that the greatest osteogenic effect occurs when the muscles act eccentrically when the force-velocity relationship indicates muscular loading is likely to be highest (38,39). A similar process may occur in cricket fast bowlers where lumbar bone adaptation is caused by the torsional loading imposed within the lower lumbar spine (21,40). Fast bowlers achieve maximum ipsilateral thoracolumbar rotation by ipsilaterally rotating from their maximum contralateral thoracolumbar rotation angle between FFC and BR. This study indicates that fast bowlers with higher lumbar BMD initiate this movement from a greater contralateral thoracolumbar rotation angle. As the thoracolumbar joint ipsilaterally rotates, the lumbopelvic joint contralaterally rotates from its maximum ipsilateral rotation angle. These opposing rotations potentially increase the torsional load upon the lumbar spine particularly on the less mobile inferior vertebrae, such as L3 and L4 (41). To resist ipsilateral rotation of the thoracolumbar spine between FFC and BR (27), eccentric contractions of the lumbar contralateral multifidus, erector spinae (42), external obliques, and contralateral internal obliques (43) may occur, contributing to the torsional load experienced by the lumbar spine. The results of this study implicate the kinematics of the thoracolumbar and lumbopelvic joint in the aetiology of lumbar bone mineral adaptations observed in this study and previous research (20) with a potential link to increased internal torsional loads proposed. Further research is necessary, however, to understand the cause-and-effect relationship between fast bowling technique and lower back torsional loads, and their aetiology in lumbar bone mineral adaptation.

In this study, greater contralateral thoracolumbar side flexion at BR was associated with increased asymmetry in BMD across L3 (Table 3), while contralateral pelvic drop at FFC was linked with greater whole lumbar BMD (Table 3; Figure 1). During the period between FFC and BR within the bowling action, contralateral side flexion of the whole trunk and pelvis occurs to ensure the bowling arm is in position to release the ball above the head (27). This happens concurrently with lumbopelvic and thoracolumbar flexion and rotations. The coupling of flexion, side flexion and rotation of the lumbar spine likely reduces the mobility of the lumbar spine (44), which has previously been associated with causing a larger amount of the torsional loading to transfer to more inferior lumbar vertebrae (45).

Osteogenic adaptations have previously been observed in other sporting movements with high vertical impacts (6–8). The external force on the body during the fast bowling action occurs during the multi-directional thoracolumbar and lumbopelvic joint kinematics previously discussed. Although VGRF was highly correlated with L1-L4 BMD, this association was not independent of individual FFM differences, and no relationships between the kinetic parameters were observed with L1-L4 BMD when FFM was included as a covariate. In addition, the asymmetry of L3 and L4 BMD was also not associated with any of the kinetic parameters, in either their normalised or absolute terms. This suggests internal loading during the fast bowling action, rather than external loading, as the predominate mechanism in the aetiology of lumbar bone mineral adaptation. External loading does not independently contribute to lumbar bone adaptation; however, it may act in combination with the internal loading, extenuating the total loading on the lumbar spine. These findings are consistent with those outlined in 'mechanostat theory' which suggests that the greatest strains generated in bone are derived from muscular rather than gravitational sources (1), although gravitational sources may contribute to the total amount of mechanical strain experienced by bone (4). In the future, research should focus on developing an understanding of both the internal load and external load mechanisms and their effect on lumbar bone mineral measures, possibly by adopting a muscle modelling approach with soft tissue movement, joint compression and muscle contraction controlled and the effects explored.

LBSI are the most prevalent injury in cricket occurring most commonly in fast bowlers (23). Two factors which have individually been associated with LBSI in fast bowlers are low BMD (20) and technique (27). While the current study associated thoracolumbar and lumbopelvic rotations in the aetiology of the unique lumbar bone adaptation observed in fast bowlers, previous research has thus far only implicated increased hip flexion at BFC and increased lumbopelvic extension at FFC in their aetiology (27). No association was found between these technique variables and L1-L4 BMD or BMD asymmetry, although larger contralateral thoracolumbar rotation angles at BFC, which may be correlated with maximal contralateral thoracolumbar rotation, have been associated with LBSI (27). This may provide evidence of a link between kinematic parameters, lumbar bone adaptation and LBSI. Meanwhile, the current finding which found no association between VGRF independent of body mass and L1-L4 BMD or asymmetry, concurs with recent research which found no differences in VGRF parameters between fast bowlers with and without LBSI (27). More research, however, is required to understand the link between technique, lumbar bone quality and LBSI in cricket fast bowlers, especially regarding the quality of bone to withstand and sustain the high workloads that are required of elite fast bowlers (19).

A strength of this research is the large number of adolescent fast bowlers recruited. These bowlers were considered fast for their age despite the recorded ball speeds being 17.2% lower than those exhibited by senior fast bowlers in another study (16). A weakness, however, is that the players have been sourced from a sample undergoing substantial hormonal and growth adaptations due to puberty, as well as potentially having different historical levels of fast bowling workload, which has the potential to skew the findings and lead to a sample bias compared to the overall fast bowling population (46).

Further limitations include adopting a discrete rather than continuous process to analyse the data, which investigates key time points rather than the whole movement pattern, and the use of absolute angles rather than relative angles normalised to the participants range of motion, which may elicit further information on the aetiology of lumbar bone mineral. Additionally, the use of 3D-based measurement outcomes instead of the 2D-based DXA used in this study may provide better resolution and allow greater understanding of lumbar bone adaptation, including bone architecture changes. Although their use with maturing individuals due to the heightened radiation exposure should be considered. Furthermore, the findings of this study are only currently applicable to male fast bowlers, thus future research should investigate the effect of fast bowling technique on female lumbar bone and stress injuries. Finally, due to the exploratory nature of the study multiple correlations and stepwise linear regression were used to investigate the relationship between the kinematic and kinetic parameters and lumbar bone mineral measures. The multiple correlations were performed without an adjustment to the alpha level since Bonferroni corrections are designed to minimise the risk of a Type 1 error, while increasing the incidence of Type 2 errors (47). As the aim of this study was exploratory this was considered inappropriate, nevertheless, these results should be treated cautiously as an increased risk of Type 1 errors occurring remains. Although the findings of the multiple regression analysis should not be compromised by multiple testing, this method does have limitations including bias in parameter estimation, multiple hypothesis testing, and reliance on a single best model. To overcome this the explained variance for all possible regression equations with the same number of predictor variables as the stepwise solution was determined for comparison.

Conclusion

This study is the first to investigate lumbar bone in adolescent male fast bowlers, and the relationship between fast bowling technique and lumbar bone adaptation. Adolescent male fast bowlers demonstrate high lumbar spine BMD, suggesting that fast bowling has a positive osteogenic effect. Similar to adult counterparts, the increase in lumbar spine BMD was asymmetric with the adaptation higher in the contralateral side of L3 and L4 compared with the ipsilateral side. These findings demonstrate that the asymmetric adaptation of the lumbar spine to fast bowling is already present in adolescent fast bowlers. Significant associations between the kinematics of the thoracolumbar and lumbopelvic joints, as well as pelvic drop, were implicated in the aetiology of bone mineral adaptation within this research. No association was found, however, between bone mineral adaptation and any of the kinetic fast bowling parameters measured, independent of body mass. This suggests that muscular forces, through the initiation and control of thoracic and lumbar rotation, are the predominant contributor to the unique asymmetric lumbar spine adaptation observed in fast bowlers. Future research should attempt to understand how technique affects loading during the fast bowling action, and its effects on lumbar bone mineral adaptation and lumbar bone stress injury.

Acknowledgments

The authors acknowledge the support of Loughborough University and England and Wales Cricket Board. The authors report no conflict of interest and the results of the present study do not constitute endorsement by ACSM. The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Supplementary File 1 – a video demonstrating the key instants of the fast bowling action (not included within this version)

Supplementary File 2 – Partial (covariate: fat free mass) and bivariate correlations between lumbar bone mineral measures and the kinematic and kinetic fast bowling parameters.

			Partial Correlation		Bivariate Correlations			
			L1-L4 BMD		L3 % difference		L4 % difference	
Parameters	Mean	SD	*r*	*P*	*r*	*P*	*r*	*P*
Kinematic parameters								
Back hip angle at BFC (˚)	151	9	0.301	0.066	0.078	0.635	-0.005	0.975
Front hip angle at FFC (˚)	134	10	0.205	0.216	0.047	0.778	-0.010	0.953
Pelvis orientation - tilt								
At BFC (˚)	188	7	0.270	0.102	0.232	0.156	-0.045	0.784
At FFC (˚)	171	6	-0.018	0.915	0.216	0.187	0.018	0.914
At BR (˚)	155	10	-0.020	0.905	0.264	0.105	0.043	0.796
Minimum (˚)	153	9	-0.022	0.895	0.257	0.115	0.078	0.637
Maximum (˚)	190	7	0.233	0.159	0.093	0.573	-0.153	0.353
Pelvis orientation - drop								
At BFC (˚)	191	7	-0.107	0.521	-0.143	0.387	-0.027	0.871
At FFC (˚)	177	5	-0.068	0.684	-0.342	**0.033***	-0.264	0.104
At BR (˚)	166	7	-0.240	0.147	-0.212	0.196	-0.209	0.203
Minimum (˚)	165	6	-0.194	0.243	-0.255	0.117	-0.243	0.137
Maximum (˚)	193	6	-0.096	0.566	-0.205	0.212	-0.051	0.756
Pelvis orientation - twist								
At BFC (˚)	233	13	0.210	0.206	0.195	0.234	0.061	0.710
At FFC (˚)	221	12	0.295	0.072	-0.103	0.533	-0.155	0.347
At BR (˚)	166	13	0.065	0.699	-0.036	0.826	-0.227	0.165
Minimum (˚)	166	13	0.067	0.691	-0.043	0.796	-0.238	0.145
Maximum (˚)	246	14	0.331	**0.042***	0.155	0.348	0.058	0.727
Lumbar angle - flexion								
At BFC (˚)	168	6	-0.079	0.638	-0.138	0.402	-0.106	0.522
At FFC (˚)	176	5	0.042	0.804	-0.010	0.953	-0.041	0.806
At BR (˚)	162	7	-0.226	0.172	0.035	0.832	-0.055	0.740
Minimum (˚)	161	6	-0.260	0.114	0.011	0.947	-0.112	0.496
Maximum (˚)	178	5	-0.038	0.823	0.050	0.764	0.055	0.741
Lumbar angle – side flexion								
At BFC (˚)	179	5	-0.112	0.504	-0.315	0.051	-0.223	0.173
At FFC (˚)	167	7	-0.197	0.236	-0.024	0.885	-0.011	0.946
At BR (˚)	172	4	-0.260	0.115	0.144	0.382	0.094	0.570
Minimum (˚)	161	5	-0.284	0.084	0.134	0.415	0.155	0.345
Maximum (˚)	181	5	-0.048	0.773	-0.211	0.197	-0.140	0.394
Lumbar angle – rotation								
At BFC (˚)	171	8	0.186	0.264	0.185	0.259	0.218	0.182
At FFC (˚)	203	9	-0.129	0.441	0.411	**0.009****	0.235	0.151
At BR (˚)	187	6	-0.037	0.825	0.290	0.073	0.460	**0.003****
Minimum (˚)	169	8	0.148	0.374	0.205	0.210	0.162	0.325

Maximum (˚)	207	10	-0.226	0.173	0.365	**0.022***	0.215	0.188
Thoracic angle - flexion								
At BFC (˚)	178	11	0.071	0.674	-0.002	0.992	0.126	0.444
At FFC (˚)	180	9	-0.008	0.963	0.111	0.503	0.178	0.279
At BR (˚)	157	11	-0.053	0.754	-0.223	0.171	-0.272	0.094
Minimum (˚)	157	11	-0.053	0.754	-0.223	0.173	-0.272	0.094
Maximum (˚)	188	9	-0.096	0.567	0.078	0.637	0.069	0.675
Thoracic angle - side flexion								
At BFC (˚)	183	5	0.325	**0.046***	0.195	0.234	0.161	0.329
At FFC (˚)	187	8	0.074	0.658	0.215	0.188	0.062	0.707
At BR (˚)	160	4	0.312	0.057	0.300	0.064	0.390	**0.014***
Minimum (˚)	157	5	0.317	0.052	0.140	0.394	0.193	0.240
Maximum (˚)	190	7	0.109	0.514	0.301	0.063	0.196	0.232
Thoracic angle - rotation								
At BFC (˚)	178	4	-0.430	**0.007****	0.009	0.958	0.079	0.632
At FFC (˚)	178	5	-0.256	0.122	-0.004	0.981	0.123	0.456
At BR (˚)	194	6	-0.008	0.960	-0.084	0.614	0.042	0.803
Minimum (˚)	174	4	-0.452	**0.004****	-0.044	0.791	-0.017	0.919
Maximum (˚)	200	7	0.031	0.852	-0.021	0.901	0.066	0.690
Kinetic parameters								
Peak vertical GRF (kN)	3.5	1.2	-0.063	0.712	0.026	0.879	-0.004	0.980
Peak vertical GRF (BW)	5.2	1.3	0.032	0.853	0.145	0.383	0.135	0.420
Vertical loading rate (kN/s)	131	90	-0.173	0.305	0.042	0.802	-0.012	0.944
Vertical loading rate (BW/s)	198	142	-0.159	0.346	0.077	0.647	0.029	0.861
Vertical impulse (N.s)	85	48	0.100	0.556	-0.099	0.554	-0.221	0.183
Vertical impulse (BW.s)	0.12	0.06	0.147	0.385	-0.018	0.913	-0.135	0.421

Abbreviations: back foot contact (BFC); front foot contact (FFC); ball release (BR), ground reaction force (GRF), body weight (BW). *P ≤ 0.050, ** P ≤ 0.010.