


Lumbar spine bone mineral adaptation: cricket fast bowlers versus controls

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ABSTRACT

Elite adult male fast bowlers have high lumbar spine bone mineral, particularly on the contralateral side to their bowling arm. It is thought that bone possesses its greatest ability to adapt to loading during adolescence, but it is unknown at what age the greatest changes in lumbar bone mineral and asymmetry develops in fast bowlers.

Objectives This study aims to evaluate the adaptation of the lumbar vertebrae in fast bowlers compared to controls and how this is associated with age.

Methods 91 male fast bowlers and 84 male controls aged 14–24 years had between one and three annual anterior-posterior lumbar spine dual-energy-X-ray absorptiometry scans. Total (L1-L4) and regional ipsilateral and contralateral L3 and L4 (relative to bowling arm) bone mineral density and content (BMD/C) were derived. Multilevel models examined the differences in lumbar bone mineral trajectories between fast bowlers and controls.

Results At L1-L4 BMC and BMD, and contralateral BMD sites, fast bowlers demonstrated a greater negative quadratic pattern to their accrual trajectories than controls. Fast bowlers had greater increases in BMC in L1-L4 between 14 and 24 years of 55% compared with controls (41%). Within vertebra, asymmetry was evident in all fast bowlers and increased by up to 13% in favour of the contralateral side.

Conclusions Lumbar vertebral adaptation to fast bowling substantially increased with age, particularly on the contralateral side. The greatest accrual was during late adolescence and early adulthood, which may correspond with the increasing physiological demands of adult professional sport.

INTRODUCTION

Bone is a dynamic material that adapts its mechanical competence through modelling and remodelling to withstand typical peak voluntary loads.^{1,2} The ability of bone to adapt to mechanical loading is enhanced during the growing years around peak height velocity³ due to synergistic increases in the amount of and effector relationships between sex hormones and insulin-like growth factors such as IGF-1.⁴ Bone strength increases occur most readily during early puberty as opposed to later or post-puberty.^{5,6} Therefore, there is great scope for increases in bone strength during this 'window of opportunity' for

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Cricket fast bowlers have substantial lumbar bone mineral and within vertebra asymmetry. However, it is unknown when or how this osteogenic adaptation develops with age.

WHAT THIS STUDY ADDS

⇒ Lumbar adaptation is evident in fast bowlers at age 14 and substantially increases during late adolescence and early adulthood.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Osteogenic adaptation likely develops with age, in addition to other factors, that must be respected when managing young athletes and preventing overuse injuries.

osteogenic adaptation to occur,⁷ which may substantively affect peak bone mass. However, the natural development of osteogenic adaptation has not been studied in an elite athletic population.

Cricket fast bowlers show remarkable adaptation in their lumbar spines as evidenced by superior L1-L4 bone mineral density (BMD) and content (BMC) compared with cricketers of other playing positions, rugby players and controls who did not regularly participate in high impact or loading resistance exercise.⁸ Additionally, fast bowlers show substantial vertebral asymmetry with up to 15% and 18% greater BMD and BMC, respectively, found on the contralateral side to the bowling arm.⁸ This reflects the asymmetrical bowling action which involves extreme multi-planar trunk movements.⁹

Fast bowlers have the greatest prevalence of injury of all the playing roles in cricket,¹⁰ with lumbar stress fracture (LSF), which occurs almost exclusively to fast bowlers, being the most prevalent injury in cricket.¹⁰ Chronological age has been considered a lumbar bone stress injury (LBSI) risk factor, with studies identifying that younger bowlers are more likely to suffer LSF between 15 and 22 years of age.^{11,12} Understanding the development



of the adaptation to fast bowling may thus be important in understanding how to prevent LBSI.

This study explored how lumbar spine BMC and BMD develop with chronological age in cricket fast bowlers. Second, this study aimed to investigate how the development of lumbar spine adaptation in fast bowlers differs to that of controls.

METHODS

Participants and ethics approval

To examine differences in lumbar BMC and BMD accrual trajectories between fast bowlers and controls through adolescence into adulthood, participants had baseline and repeat dual-energy-X-ray absorptiometry scans (DXA) which were compared through multilevel growth curve models.

A total of 91 male fast bowlers aged 14–24 years inclusive were recruited through England and Wales Cricket Board (ECB) senior and pathway teams (adult bowlers cohort: n=50), as well as professional county cricket clubs, and schools and clubs with well-developed cricket programmes (adolescent bowlers cohort: n=41). Fast bowlers were defined as those who bowled at least 10% of their teams' overs, who the wicket keeper stands back for, aged 14 or over with at least 2 years' experience in high-level cricket. Active male field sport controls were recruited from sporting academies, local schools with strong sporting programmes (adolescent control cohort: n=11), and university teams (adult control cohort: n=32). Control participants did not participate in cricket or asymmetrical loading sports such as tennis or hockey. Furthermore, comparator data from 41 adolescent controls aged 14–17 years were used from another study (The ALPHABET Study).¹³ All participants received a baseline DXA scan and were invited for follow-up scans annually on up to three occasions. 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.

Written informed consent, or assent from a parent or guardian of participants under 16 years old, was obtained prior to inclusion in the study.

DXA

Each participant received an anterior-posterior (AP) lumbar spine and total body DXA scan (GE Lunar iDXA, GE Healthcare, USA) during the cricket preseason or postseason. Controls from The ALPHABET study received an AP lumbar spine DXA scan (GE Lunar iDXA, GE Healthcare, USA) at several UK sites. Total body scans were used to determine the fat-free mass (FFM). AP lumbar spine scans were analysed to determine total (L1-L4) and regional BMD and BMC and Z-scores (Lunar enCore v17, GE Healthcare, USA). A custom analysis was used to determine the contralateral (C) and ipsilateral (I) sides of the spine, using the most lateral 33% of the vertebral body at L3 and L4.⁸ Vertebral asymmetry was calculated as $[(\text{contralateral} - \text{ipsilateral}) / \text{ipsilateral}] * 100$; such that a positive value indicates a greater value on the contralateral side.

Analysis

The medians and IQRs for participant characteristics of age, height, weight, FFM, L1-L4 BMD and BMC, and the means and SD for each recruitment group were calculated (table 1).

Multilevel growth curve models (observations at level one and individuals at level two) with two-degree fractional polynomial functions of age were used to examine differences in lumbar BMC, BMD and within vertebra asymmetry trajectories between fast bowlers and controls. In each model, intercepts were allowed to vary between individuals (ie, random intercept) while slopes were not. A binary exposure (activity) interacted with the two fractional polynomial terms. FFM was used as a covariate for all models as lean tissue mass strongly associates with bone mineral measures.^{14 15} A fractional polynomial is an automated procedure that runs a series of models to determine the best powers to raise an independent variable (ie, age) to produce the best-fitting smooth trajectory.

Table 1 Participant characteristics for each cohort recruited to the study at baseline

Cohort		Age (years)	Height (cm)	Body mass (kg)	FFM (kg)	L1-L4 BMD Z-Score
<i>Fast bowlers</i>						
Adolescents	Mean±SD	15.6±1.1	179.5±6.9	68.70±10.49	56.66±8.07	0.84±1.19
Adults	Mean±SD	19.3±1.9	188.1±6.2	82.76±9.53	69.36±6.96	1.87±1.17
All	Median (IQR)	17.6 (15.7–18.8)	183.8 (179.6–189.0)	76.50 (69.27–84.55)	63.14 (58.02–70.31)	1.30 (0.50–2.35)
<i>Controls</i>						
Adolescents	Mean±SD	15.8±0.9	179.2±4.7	73.46±10.70	58.36±5.81	0.92±0.75
Alphabet study	Mean±SD	15.6±1.1	177.6±7.2	67.44±10.02	53.42±7.79	0.19±0.82
Adults	Mean±SD	20.4±1.4	182.0±5.4	78.06±7.43	66.46±5.56	0.95±0.76
All	Median (IQR)	16.7 (15.4–19.5)	179.9 (175.5–184.0)	73.60 (65.45–79.28)	58.54 (53.74–66.02)	0.61 (–0.20–1.20)

BMD, bone mineral density; FFM, fat-free mass.

With a two-degree fractional polynomial and the default set of powers (-2, -1, -0.5, 0, 0.5, 1, 2, 3), there are two age terms and 36 models are tested. The model with the lowest deviance is chosen and used in further analyses. The fractional polynomial multilevel models were run for each outcome using the `fp` command in Stata IC16 (College Station, Texas, USA). The final growth curve models were run in MLwiN (MLwiN, V.3.05, University of Bristol, UK).

Level 1 and 2 standardised residuals were visually examined using Q-Q plots and plotted against age to determine normality (online supplemental file 1). Anomalous data and analyses where the spinous process encroached into the regions of interest of ipsilateral and contralateral measurements of L3 and L4 were excluded. Plots were produced demonstrating the sample average trajectories for each group with 95% CI. The final model formula for each BMD and BMC variable was explained by:

Where y_{ij} is

$$y_{ij} = \beta_{0ij} + \beta_1 \text{Age}_{ij}^{\beta_1} + \beta_2 \text{Age}_{ij}^{\beta_2} + \beta_3 \text{Activity}_j + \beta_4 \text{Age}_{ij}^{\beta_1} \text{Activity}_j + \beta_5 \text{Age}_{ij}^{\beta_2} \text{Activity}_j + \beta_6 \text{FFM}(gm)_{ij} + e_{ij}$$

$$\beta_{0ij} = \beta_0 + u_{0j} + e_{ij}$$

$$[U_{0j}] \quad N(0, \Omega_u) : \Omega_u = [\sigma_{u0}^2] \quad [e_{ij}] \quad N(0, \Omega_e) : \Omega_e = [\sigma_e^2]$$

The final model formula for each BMD and BMC asymmetry variable was explained by:

Where y_{ij} is

$$y_{ij} = \beta_{0ij} + \beta_1 \text{Age}_{ij}^{\beta_1} + \beta_2 \text{Activity}_j + \beta_3 \text{Age}_{ij}^{\beta_1} \text{Activity}_j + \beta_4 \text{FFM}(gm)_{ij} + e_{ij}$$

$$\beta_{0ij} = \beta_0 + u_{0j} + e_{ij}$$

$$[U_{0j}] \quad N(0, \Omega_u) : \Omega_u = [\sigma_{u0}^2] \quad [e_{ij}] \quad N(0, \Omega_e) : \Omega_e = [\sigma_e^2]$$

RESULTS

A total of 286 observations were available from 175 participants. The mean±SD age at the first scan was 17.60±2.46 in fast bowlers and 17.45±2.64 in controls. The ethnicity of participants was similar across groups: 85 White (93.4%) and 6 Asian (6.6%) fast bowlers and 79 White (94.0%) and 5 Asian (6.0%) controls. In fast bowlers, the numbers with one, two, three, four and six observations were 37, 41, 30, 1 and 1, respectively. Control's corresponding numbers were 54, 22, 4, 4 and 0.

Lumbar bone growth curve models

Anomalous data, or analyses where the spinous process encroached into the regions of interest, were excluded

from the models of CL3 BMD (two observations), L3 BMD asymmetry (one observation), IL4 BMD (two observations), CL4 BMD (two observations), L4 BMD asymmetry (four observations), IL3 BMC (one observation), CL3 BMC (seven observations), L3 BMC asymmetry (eight observations), CL4 BMC (two observations) and L4 BMC asymmetry (four observations). Following the exclusion of data, all models were normally distributed (online supplemental file 1). The powers and final models for each variable can be found in online supplemental file 2.

At age 14, negligible or small differences in BMD and BMC were observed between groups for any L1-L4 or unilateral measure (tables 2 and 3, figures 1–3). Throughout mid to late adolescence and into early adulthood, at L1-L4, and in particular, at contralateral sites, fast bowlers demonstrated greater BMD and BMC than controls (figures 1–3). At age 14, large differences in asymmetry were observed at both L3 (BMD Asymmetry %: $\beta=9.60$, 95% CI 4.67 to 14.53; BMC Asymmetry %: $\beta=14.30$, 95% CI 10.28 to 18.31) and L4 (BMD Asymmetry %: $\beta=7.58$, 95% CI 4.17 to 11.00; BMC Asymmetry %: $\beta=12.83$, 95% CI 9.14 to 16.53), where fast bowlers demonstrated greater contralateral side dominant asymmetry compared with controls (tables 2 and 3). The differences between groups in asymmetry are maintained with increasing age for L3 BMD and BMC and continue to increase in magnitude for L4 BMC and BMD.

Between 14 and 24 years, fast bowlers demonstrated between 19.7% and 34.7% increment in L1-L4 and unilateral BMD (figures 1 and 3), a 55.2% increment in L1-L4 BMC (figure 1), between 34.8% and 53.3% increment in unilateral BMC (figure 2), and a 3.0%–12.6% increment in BMC and BMD asymmetry at L3 and L4. Between 14 and 24 years, controls demonstrated between 22.7% and 25.8% increment in L1-L4 and unilateral BMD (figures 1 and 3), a 40.6% increment in L1-L4 BMC (figure 1), between 15.8% and 20.3% increment in unilateral BMC (figure 2), and a -3.2%–6.0% change in BMC and BMD asymmetry at L3 and L4.

At L1-L4 BMD, fast bowlers demonstrated a greater negative quadratic pattern to their trajectories compared with controls ($\beta^{\text{P1}}=-967$, 95% CI -1771 to -163, $\beta^{\text{P2}}=397$, 95% CI 56 to 738; table 2, figure 1) indicating a greater increase in bone mineral at a younger age. This was underpinned by a similar pattern at contralateral BMD sites (CL3: $\beta^{\text{P1}}=-84.53$, 95% CI -193.45 to 24.39, $\beta^{\text{P2}}=37.06$, 95% CI -14.55 to 88.67; CL4: $\beta^{\text{P1}}=6.44$, 95% CI -0.67 to 13.55, $\beta^{\text{P2}}=-1.28$, 95% CI -2.73 to 0.17), but not at ipsilateral sites (IL3: $\beta^{\text{P1}}=-9.02$, 95% CI -59.96 to 41.92, $\beta^{\text{P2}}=-0.96$, 95% CI -6.96 to 5.04; IL4: $\beta^{\text{P1}}=1.50$, 95% CI -4.46 to 7.46, $\beta^{\text{P2}}=-0.76$, 95% CI -3.56 to 2.04; table 2, figure 3). L1-L4 BMC also demonstrated a greater negative quadratic pattern compared with controls ($\beta^{\text{P1}}=-70.75$, 95% CI -143.74 to 22.41, $\beta^{\text{P2}}=28.55$, 95% CI -2.36 to 59.46; table 3, figure 1). However, there were only small differences in trajectories between groups at unilateral BMC sites (IL3: $\beta^{\text{P1}}=-4181$, 95% CI -11 990 to 3628, $\beta^{\text{P2}}=1597$, 95% CI -1721 to 4915; CL3: $\beta^{\text{P1}}=-3775$,

Table 2 Age term estimates (95% CI) from multilevel models for each BMD variable

Parameter	L1-L4 BMD	IL3 BMD	CL3 BMD	L3 BMD asymmetry	IL4 BMD	CL4 BMD	L4 BMD asymmetry
Constant	1.113 (1.040 to 1.186)	1.234 (1.150 to 1.318)	1.280 (1.190 to 1.370)	-0.57 (-4.84 to 3.70)	1.253 (1.171 to 1.335)	1.285 (1.193 to 1.377)	-0.15 (-3.03 to 2.74)
Age ^{p1}	-114.98 (-812.31 to 582.35)	-63.99 (-105.68 to -22.30)	-16.49 (-106.98 to 74.00)	965 (-1126 to 3056)	5.75 (0.89 to 10.61)	3.16 (-2.72 to 9.04)	-0.006 (-0.023 to 0.011)
Age ^{p2}	15.92 (-278.63 to 310.47)	-6.87 (-11.77 to -1.97)	2.92 (-39.85 to 45.69)	-	-2.39 (-4.66 to -0.12)	-0.59 (-1.79 to 0.61)	-
Covariate							
FFM	0.0046 (0.0024 to 0.0068)	0.0076 (0.0049 to 0.0103)	0.0067 (0.0038 to 0.0096)	-0.0916 (-0.2592 to 0.0760)	0.0094 (0.0065 to 0.0123)	0.0085 (0.0054 to 0.0116)	-0.079 (-0.222 to 0.065)
Group (Control as Reference)							
FB	-0.012 (-0.094 to 0.070)	-0.025 (-0.125 to 0.075)	0.068 (-0.038 to 0.174)	9.600 (4.667 to 14.533)	0.036 (-0.062 to 0.134)	0.085 (-0.025 to 0.195)	7.58 (4.17 to 11.00)
Interaction effects (Control as Reference)							
FB × Age ^{p1}	-967 (-1771 to -163)	-9.02 (-59.96 to 41.92)	-84.53 (-193.45 to 24.39)	-1876 (-4285 to 533)	1.50 (-4.46 to 7.46)	6.44 (-0.67 to 13.55)	0.040 (0.020 to 0.060)
FB × Age ^{p2}	397 (56 to 738)	-0.96 (-6.96 to 5.04)	37.06 (-14.55 to 88.67)	-	-0.76 (-3.56 to 2.04)	-1.28 (-2.73 to 0.17)	-
Random							
Between individual variance	0.017 (0.013 to 0.021)	0.020 (0.016 to 0.024)	0.023 (0.017 to 0.029)	67.07 (51.62 to 82.51)	0.020 (0.016 to 0.024)	0.030 (0.024 to 0.036)	50.95 (39.10 to 62.81)
Within individual variance	0.0006 (0.0004 to 0.0008)	0.0023 (0.0017 to 0.0029)	0.0019 (0.0013 to 0.0025)	8.63 (6.36 to 10.90)	0.0023 (0.0017 to 0.0029)	0.0020 (0.0014 to 0.0026)	7.03 (5.15 to 8.90)
-2*loglikelihood	-647	-469	-455	1865	-465	-411	1778
BMD, bone mineral density; CL, contralateral; FB, fast bowler; FFM, fat-free mass; IL, ipsilateral.							

Table 3 Age term estimates (95% CI) from multilevel models for each BMC variable. L1-L4 BMC in kg

Parameter	L1-L4 BMC	IL3 BMC	CL3 BMC	L3 BMC asymmetry	IL4 BMC	CL4 BMC	L4 BMC asymmetry
Constant	0.064 (0.057 to 0.071)	5.58 (5.01 to 6.15)	5.42 (4.83 to 6.01)	-6.98 (-10.36,-3.61)	6.19 (5.56 to 6.82)	6.10 (5.39 to 6.81)	-4.36 (-7.51 to -1.20)
Age ^{p1}	-30.71 (-94.29 to 32.87)	-6253 (-12 611 to 105)	-2597 (-9149 to 3955)	0.0005 (-0.0003 to 0.0013)	-8101 (-15 110 to -1092)	-5172 (-12 824 to 2480)	0.0064 (-0.0122 to 0.0250)
Age ^{p2}	9.58 (-17.26 to 36.41)	2517 (-182 to 5216)	955 (-1826 to 3736)	-	3297 (322 to 6272)	2053 (-1195 to 5301)	-
<i>Covariate</i>							
FFM	0.0005 (0.0003 to 0.0007)	0.069 (0.051 to 0.087)	0.062 (0.042 to 0.082)	-0.201 (-0.381 to -0.020)	0.073 (0.053 to 0.093)	0.067 (0.045 to 0.089)	-0.130 (-0.291 to 0.032)
<i>Group (Control as Reference)</i>							
FB	0.0020 (-0.0056 to 0.0097)	-0.62 (-1.31 to 0.07)	0.09 (-0.62 to 0.80)	14.30 (10.28 to 18.31)	-0.49 (-1.25 to 0.27)	0.03 (-0.79 to 0.85)	12.83 (9.14 to 16.53)
<i>Interaction effects (Control as Reference)</i>							
FB × Age ^{p1}	-70.75 (-143.74 to 22.41)	-4181 (-11 990 to 3628)	-3775 (-11 876 to 4326)	0.0003 (-0.0007 to 0.0013)	-2046 (-10 656 to 6564)	-4495 (-13 838 to 4848)	0.0200 (-0.0023 to 0.0423)
FB × Age ^{p2}	28.55 (-2.36 to 59.46)	1597 (-1721 to 4915)	1358 (-2086 to 4802)	-	736 (-2923 to 4395)	1661 (-2310 to 5632)	-
<i>Random</i>							
Between individual variance	0.00015 (0.00012 to 0.00018)	0.683 (0.520 to 0.846)	0.720 (0.546 to 0.894)	68.24 (50.93 to 85.54)	0.824 (0.626 to 1.022)	1.070 (0.817 to 1.323)	48.47 (35.61 to 61.34)
Within individual variance	0.000005 (0.000003 to 0.000006)	0.125 (0.092 to 0.158)	0.134 (0.099 to 0.169)	16.89 (12.36 to 21.42)	0.153 (0.112 to 0.194)	0.158 (0.117 to 0.199)	15.66 (11.50 to 19.82)
-2*loglikelihood	1941	602	608	1909	660	700	1876
BMC, bone mineral content; CL, contralateral; FB, fast bowler; FFM, fat-free mass; IL, ipsilateral.							

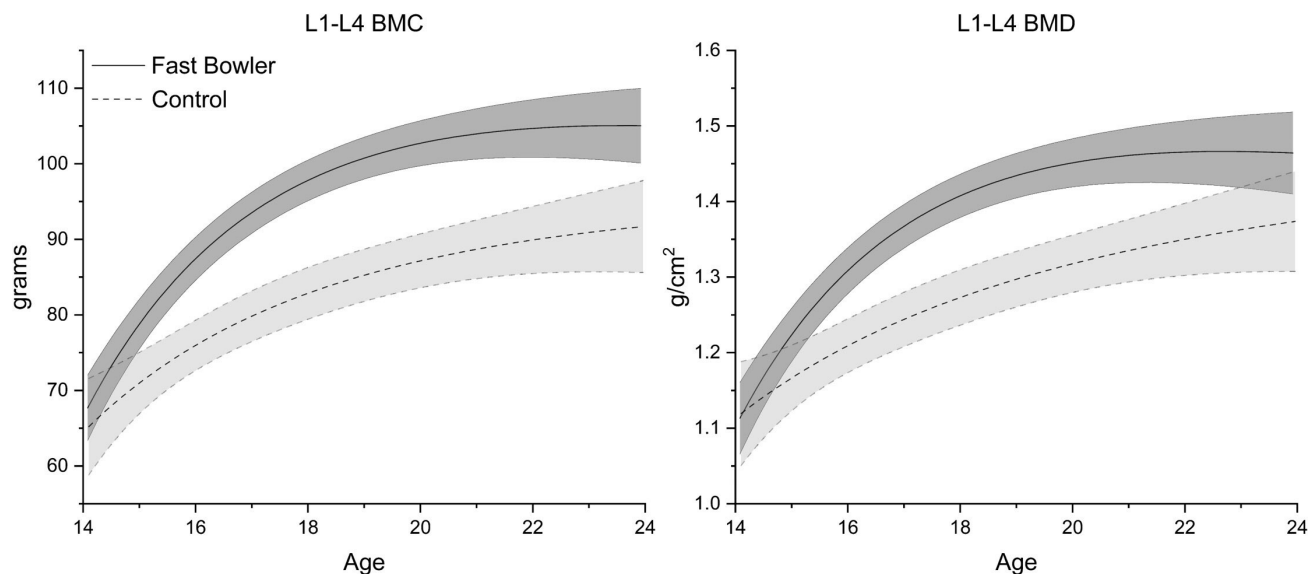


Figure 1 Mean (95% CI) L1-L4 BMC and BMD trajectories for fast bowlers and controls. Trajectories adjusted for fat-free mass. BMC, bone mineral content; BMD, bone mineral density.

95% CI $-11\ 876$ to 4326 , $\beta^2=1358$, 95% CI -2086 to 4802 ; IL4: $\beta^1=-2046$, 95% CI $-10\ 656$ to 6564 , $\beta^2=736$, 95% CI -2923 to 4395 ; CL4: $\beta^1=-4495$, 95% CI $-13\ 838$ to 4848 , $\beta^2=1661$, 95% CI -2310 to 5632 ; table 3, figure 2). The greatest increases in BMD and BMC were observed during mid to late adolescence (figures 1–3). Fast bowlers generally demonstrated a greater positive near linear pattern to their trajectories in asymmetry at L3 and L4 in BMD and BMC, in particular at L4 (L3 BMD Asymmetry: $\beta^1=-1876$, 95% CI -4285 to 533 ; L3 BMC Asymmetry: $\beta^1=0.0003$, 95% CI -0.0007 to 0.0013 ; L4 BMD Asymmetry: $\beta^1=0.04$, 95% CI 0.02 to 0.06 ; L4 BMC Asymmetry: $\beta^1=0.020$, 95% CI -0.002 to 0.042 , tables 2 and 3).

DISCUSSION

This study was the first to prospectively explore the natural development of sport-specific skeletal adaptation in fast bowlers, a unique athletic population subject to high magnitude, asymmetric loading. Within vertebra asymmetry was evident in all fast bowlers at age 14 and increased by up to 13% in favour of the contralateral side in early adulthood. The highest bone mineral in fast bowlers was observed between 20 and 24 years and tended to increase earlier than in controls, especially on the contralateral side. Fast bowlers also gained a greater amount of bone mineral resulting in 35% greater BMD and 55% greater BMC at adulthood than age 14, compared with only up to 26% and 41% greater BMD and BMC, respectively, in controls. The differences in bone mineral between the groups were independent of FFM, indicating that the lumbar bone mineral adaptation in fast bowlers is due to the internal and external loading of the sport and not mediated through differences in musculature or body size.

Fast bowlers exhibited substantial adaptation in their lumbar spine, for example, substantial side-to-side differences in bone mineral within vertebra. This asymmetry

markedly increased between 14 and 20 years of age, reaching the highest point in this cohort between 20.5 and 24 years. This is an example of exercise-induced osteogenic adaptation in which impact-loading sports facilitate greater total body and site-specific bone mineral in adolescents and adults compared with active-loading sports and inactive individuals.^{16–18} The differences in bone mineral adaptation with age mirror the natural change in bone mineral, with great gains in the adolescent growing years (between 13 and 17)¹⁹ and smaller increases as bone mass velocity starts to reduce around 18 years of age,²⁰ until skeletal maturation of the lumbar spine in the third decade.^{21–22} Until this point, the immature bone may attenuate forces to a lesser extent and be less robust to high bowling volumes or techniques which load the lumbar spine to a greater extent, which may be why higher LBSI rates are seen in younger fast bowlers.^{11–12}

Early fast bowling adaptation, in terms of higher lumbar BMD and BMC and greater within-vertebra asymmetry in favour of the contralateral side, is already present in 14-year-olds, the youngest bowlers recorded in this cohort, which invites further questions as to when this adaptation begins. Due to the substantial loading in fast bowling, it is likely that the osteogenic adaptation identified in this study would develop as soon after first participation in the activity, which could be enhanced and facilitated by other asymmetrical loading sports. Thus, future research should examine the effect of starting age and the possible effect of other sports and activities on lumbar bone mineral adaptation in fast bowlers. Adaptation to tennis has been detected in 7–8-year-olds,²³ and studies of intra-arm asymmetry in prepubescent racquet sport players show that adaptation indeed develops at a young age during early adolescence.^{24–26} The younger bowlers in this cohort will likely have passed through the window of opportunity during early puberty, before inclusion in

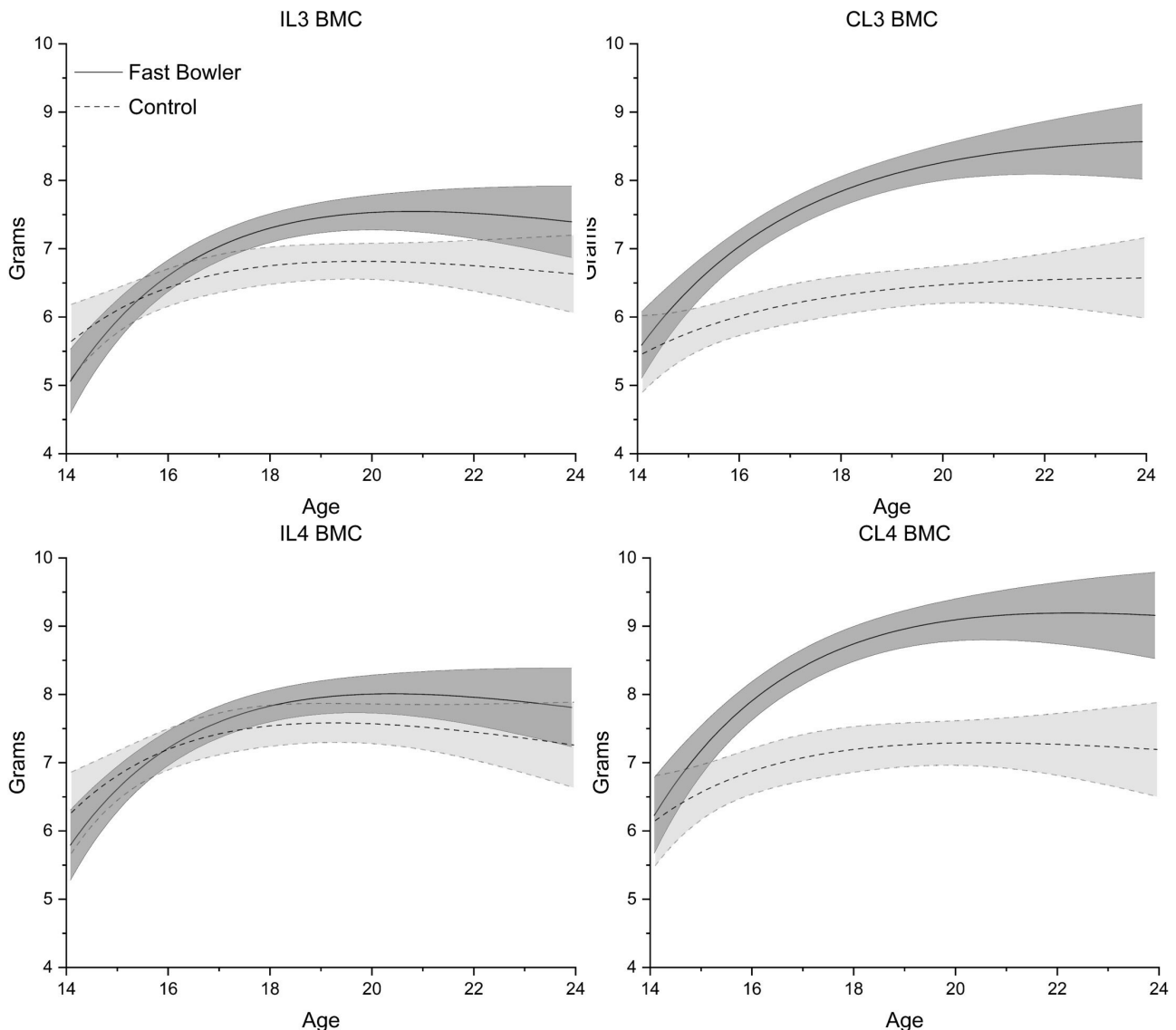


Figure 2 Mean (95% CI) ipsilateral and contralateral L3 (IL3 and CL3) and L4 (IL4 and CL4) BMC trajectories for fast bowlers and controls. Trajectories adjusted for fat-free mass. BMC, bone mineral content; BMD, bone mineral density.

the study, for increases in bone mass and strength.⁷ This suggests that the loading of fast bowling elicits substantial changes in the lumbar spine of adolescents in addition to maturational changes and those in response to changes in body size and hormonal changes.

The age at which bone mineral seemed to be at its highest in the fast bowlers in early adulthood was also earlier than that of controls, possibly relating to the fact that this sporting movement is predominantly performed by taller individuals who may have matured earlier than others their age. The increase in bone mineral in fast bowlers may reflect the increasing age-related bowling volume guidelines that are present in England and Wales.²⁷ These aim to gradually increase bowling volume from a maximum of 60 deliveries per day at age 13, to 108 by age 19, implying that much of the adaptation to fast bowling occurs when bowling volumes increase with age. Additionally, when fast bowlers begin playing professional cricket, the loading volume and intensity increase,

and they may undergo substantial physical conditioning. Thus, muscular strength and body size change, may contribute to the osteogenic adaptation during this time.

The unique lumbar bone mineral adaptation to fast bowling is particularly evident on the contralateral side of the lumbar spine, suggesting that the asymmetrical nature of the bowling action facilitates marked adaptation on the contralateral side of the lumbar spine, which is not seen in non-active controls and field sport athletes. The adaptation of the lumbar spine to fast bowling is driven by the forceful rotations of the thoracic and lumbar spine between back foot contact and ball release of the bowling action.⁹ This movement likely imparts a torsional force and high bone strain in the posterior elements of the vertebrae,²⁸ resulting in the osteogenic adaptation identified. Although external loads such as ground reaction forces showed no significant relationship to BMD,⁹ it is possible that they contribute to the adaptation by influencing the internal loading of the

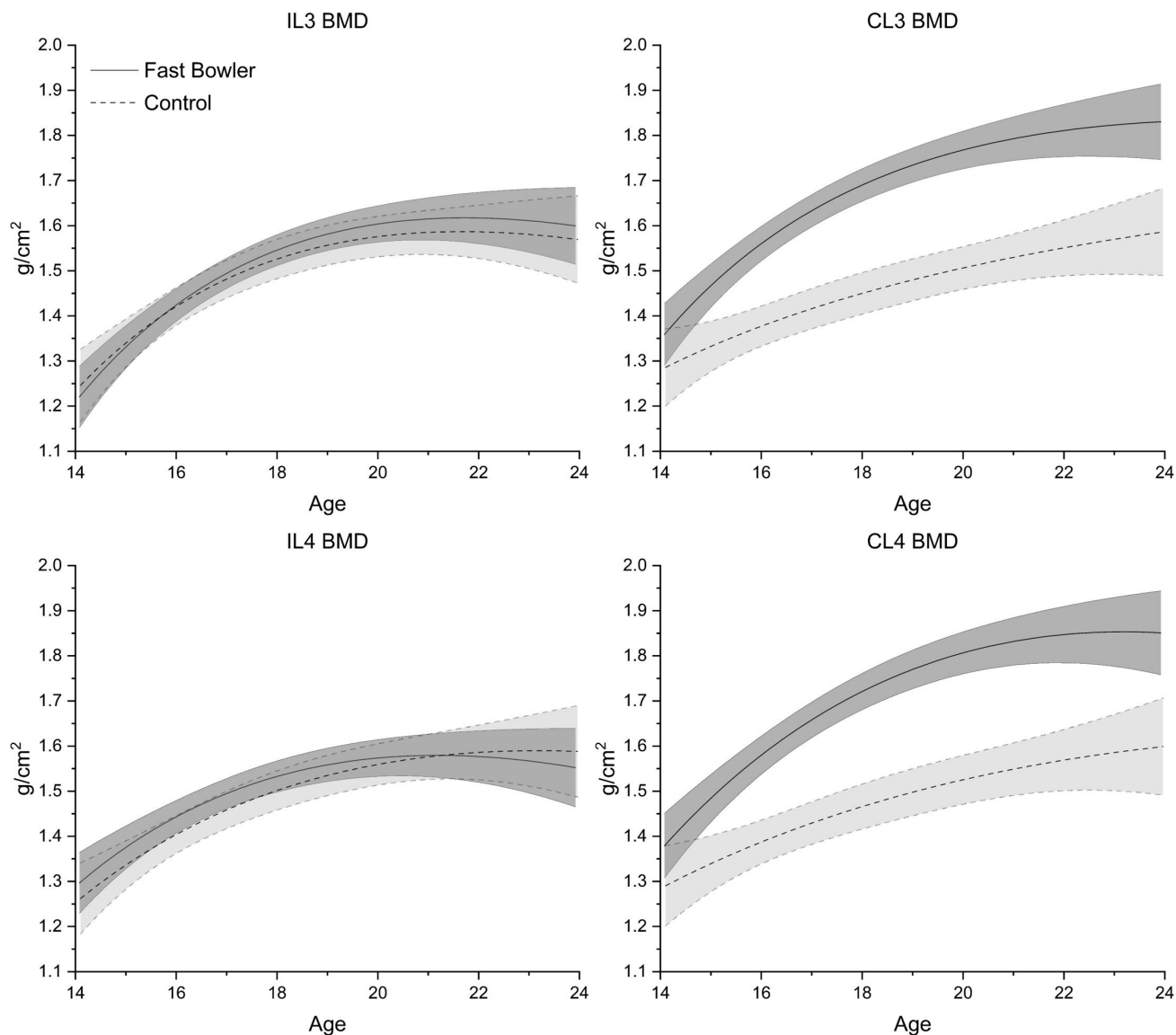


Figure 3 Mean (95% CI) ipsilateral and contralateral L3 (IL3 and CL3) and L4 (IL4 and CL4) BMD trajectories for fast bowlers and controls. Trajectories adjusted for fat-free mass. BMC, bone mineral content; BMD, bone mineral density.

lumbar spine. The unique adaptation of fast bowlers compared with other sporting and non-sporting controls was established previously in senior populations^{8,29} and adolescents⁹ and has been assessed longitudinally in this study for the first time.

Implications

The findings of this study provide evidence for the management of younger athletes, with regard to the optimisation of bone mineral to ensure resilience to sports providing high skeletal loading. It indicated that adaptation likely develops with age, via biological changes and increases in loading volume and magnitude, and that exercise loading must potentially be managed in accordance with age in the less mature skeleton to prevent overuse injury. Moreover, the study shows that loading before and during adolescence produces substantial sports-specific adaptation. Thus,

athletes whose training was curtailed during this period may have less skeletal resilience and increased injury risk. Our previous research has demonstrated that young fast bowlers have increased injury risk, particularly as they start competing at senior level,³⁰ and that injury risk is associated with lower skeletal robustness³¹ and high bowling volume,¹² in conjunction with inadequate rest periods.³² It is thus important to progressively increase loading magnitude to achieve skeletal resilience in adolescence while controlling bowling volume and incorporating adequate rest to reduce injury risk. The research provides the basis for further investigation into the longitudinal changes in the skeleton in athletic populations, how this relates to loading characteristics such as training volume and intensity, and injury risk, and whether such gains occur in individuals that come to the sport later.

Strengths and limitations

This study provided the first investigation of lumbar bone mineral development in an athletic population. The use of elite fast bowlers, extensive range of participant ages and group numbers is a strength of the study, as is the use of multilevel modelling, which can include multiple observations for each participant and account for intraindividual and interindividual variation. Due to the nature of elite cricket, observations were not measured at equal intervals in all participants and seasonal differences in DXA measurement time were not accounted for. Although participants in the adolescent fast bowling cohort and the adolescent control cohort from the Alphabet study were age, gender, height, weight and ethnicity matched, all other participants were heterogeneous in these characteristics. This may have influenced lumbar bone mineral changes, although such effects are likely to be considerably smaller than those associated with fast bowling. The study may also be limited because scans were analysed by three different researchers. However, it is not likely that variability between researchers will have affected results as they followed a rigorous methodology previously examined to be reproducible between observers.³³ Additionally, there is a downturn in BMC/D at older ages in some models, which seems implausible and is most likely due to the use of the quadratic model and fewer data points in this range which skew the data. Further research should examine the relationship between osteogenic adaptation with skeletal maturation and career bowling volume history, which may have improved model fit, but was omitted from this study due to the lack of reliable measurement in most participants. Additionally, future research should examine the sport-specific induced adaptation in individuals from when they begin partaking in the sport, as well as investigating these relationships in women and other sports. This will provide a greater understanding of the development of skeletal adaptation in sporting populations and provide foundations for associations with age-related sporting workload, intensity or injury risk.

CONCLUSION

In conclusion, fast bowlers had increases in BMC in L1-L4 between 14 and 24 years of age of 55% compared with controls who gained 41%. Bone mineral in fast bowlers increased substantially between 14 and 20 years and tended to increase earlier than in controls, especially on the contralateral side to the bowling arm. Within vertebra asymmetry was evident in all fast bowlers and increased by up to 13% in favour of the contralateral side from age 14 to 24. The results of this study suggest that fast bowling loading characteristics have a greater osteogenic effect, particularly on the contralateral side of the lumbar spine, compared with day-to-day external loading or loading of field sports. Yet, this substantial loading should be balanced with rest and controlled bowling volumes to allow optimal, healthy adaptation and reduce risk of injury. Adolescence is a critical time in the skeletal

development of a fast bowler. These relationships highlight the need to be aware that while younger athletes have already developed substantial skeletal adaptation, they are still not as robust as their senior counterparts who have had several years to adapt to loading, before and after skeletal maturity. Adolescent athletes may thus be at an increased risk of skeletal injury. Future research should aim to assess the longitudinal effects of exercise loading on the skeleton and how it may relate to skeletal injury risk.

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