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Bone

Full Length Article

Lumbar bone mineral asymmetry in elite cricket fast bowlers

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ABSTRACT

Purpose: Bone responds to mechanical loading by increasing bone mineral density (BMD) and/or bone area to enhance bone strength at the site of the greatest strain. Such localised adaptation has not been demonstrated at the spine. The aim of this study is to determine if BMD and/or bone mineral content (BMC) differs between dominant (ipsilateral to bowling/throwing arm) and non-dominant sides of the vertebrae in cricket fast bowlers, and whether this asymmetry differs according to stress fracture or disc injury history. A further aim was to determine if regional BMD and BMC in the lumbar spine differ between fast bowlers, other cricketers, rugby players and non-active controls, to highlight the site-specific response of lumbar vertebra to unilateral activity.
Methods: 23 fast bowlers, 14 other cricketers, 22 rugby players and 20 controls underwent an antero-posterior (AP) and lateral DXA scans of their lumbar spine to assess BMD, BMC and area. A custom analysis measured BMD and BMC of the dominant and non-dominant sides (lateral 33%) of the AP lumbar spine. BMD and BMC were compared between groups, injury status, vertebrae and sides using ANOVA.
Results: Analysis of medical records showed that 6 fast bowlers had a history of lumbar stress fracture. Significantly greater BMD and BMC was found in the L4 non-dominant vertebra compared with the dominant vertebra in fast bowlers. BMD and BMC differed significantly according to vertebra, side and group, with fast bowlers having significantly greater BMD and BMC at the L3 and L4 non-dominant vertebra compared with other groups (L3: 13.3%–45.3%, L4: 15.7%–44.0%) compared with other groups. Fast bowlers who never suffered lumbar stress fracture had 3.6% and 1.7% greater BMD in the dominant and non-dominant sides of lumbar vertebrae respectively compared with those who did suffer lumbar stress fracture, but evidence of this was weaker ($P = 0.08$).
Conclusion: The lumbar spine responds to a unique unilateral high loading activity through site-specific increased bone mass at the site of most strain. Fast bowlers had increased lumbar BMD, particularly on the non-dominant side of L4, although this adaptation was less marked in those with history of lumbar stress fracture. Site-specific low bone mineral density within the lumbar side may be implicated in the aetiology of lumbar stress fracture.

1. Introduction

Cricket fast bowling is a unique unilateral movement pattern defined by extreme multi-planar trunk movements > 125% of active range of motion [1], high vertical ground reaction forces in excess of 7 times body weight at front foot contact [3] and high match workloads > 2400 deliveries in a season [4], contributing to a large lumbar load, where peak lumbar forces can exceed $20 \, N/kg^{-1}$ and peak lumbo-pelvic moments can exceed of $10 \, Nm/kg^{-1}/m^{-1}$ per delivery in all three directions [5].

Bone is a remarkable material capable of responding to its mechanical environment to balance the efficiency of locomotion with strength of the bone [6]. This response may be governed by a 'mechanostat' [7] which optimises mass and architecture of bone through modelling [8] and remodelling [9] processes to ensure that typical local peak bone strains are minimized to keep strains below the microdamage threshold, preventing acute or fatigue fractures [10]. Where typical peak mechanical strains exceed the microdamage threshold, microdamage can escape usual repair, accumulating and coalescing, increasing fragility and increasing the risk of sustaining a stress fracture

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[11].

Site-specific response of bone to a stressful mechanical environment can be observed in male tennis and baseball players, whose playing arms demonstrate significantly greater BMD and BMC of up to 24% and 45% respectively compared with their non-playing arms [12–19]. This response was suggested to be due to the osteogenic effect of the muscles surrounding the shoulder, elbow and wrist acting upon the bones of the arm, producing a large mechanical strain, stimulating a response [20]. The response of the lumbar spine to stressful mechanical environment can be observed in male rugby players, who demonstrate significantly elevated BMD and BMC at the lumbar spine than a control population [21,22] in response to the high bilateral forces sustained by the trunk during collisions, tackling and while scrummaging [23,24].

While it is known that cricketers demonstrate significantly greater lumbar spine BMD than physically active controls, lumbar BMD and BMC did not differ between fast bowlers, batters or spin bowlers [25]. However, this study had few participants per group, and participants were all young adults (mean age of 22 years), and may not have reached peak bone mass or elite playing status. Incidence of lumbar stress fracture (LSF) is high in fast bowlers, with up to 67% having a history of LSF across their career [26]. LSF are most prevalent at the fourth and fifth lumbar vertebra (66% of all incidence), with 93% of all LSF occuring at the neural arch on the non-dominant side (contralateral to bowling arm, [27]). This unilateral injury may be a result of the increased stress placed on this area, with a finite element analysis estimating that stresses within the neural arch on the non-dominant side of L4 are up to 10% greater than on the dominant side [28]. This suggests that fast bowlers may exceed the microdamage threshold of the L4 and L5 non-dominant lumbar spine possibly as a result of local maladaptation to their extreme mechanical environment. The inability of bone to respond to its mechanical environment has been suggested to be a risk factor to stress fracture in endurance runners [29]. Another common injury in fast bowlers are injuries to the intervertebral discs of the lumbar spine, with up to 61% of fast bowlers demonstrating abnormalities on MRI [30].

It is not known whether a site specific response to mechanical loading is present in the lumbar spine of fast bowlers, or if maladaptation is a risk factor to LSF or disc injuries in fast bowlers. The aim of this study was to determine if BMD and/or BMC differs between dominant and non-dominant sides of the vertebrae in cricket fast bowlers, if whole and regional BMD and BMC differs between different groups, and whether BMD and BMC differs according to stress fracture or disc injury history.

2. Methods

2.1. Experimental design

The study was cross-sectional, with measurements being made during one visit to the laboratory. The study was approved by the Loughborough University Ethics Advisory Committee and National Research Ethics Service (NRES). All participants provided written informed consent and ethics was obtained from both the National Research Ethics Service and Loughborough University Ethics Approvals (Human Participants) Sub-Committee.

2.2. Participants

Participants included 37 elite male cricketers (23 fast bowlers, 14 other cricketers (11 batters, 2 wicketkeepers, 1 spin bowler), 22 rugby players and 20 control participants. Inclusion criteria for the cricketers were participation in national senior or developmental squads. Fast bowlers were defined as those who the wicketkeeper would usually "stand back". Inclusion criteria for the rugby players were to regularly train or compete at least 3 times a week for at least the last six months and compete in a minimum of university standard. Inclusion criteria for

the controls were no regular participation in high impact or loading resistance exercise. Exclusion criteria for all participants were any disease or medication that affects bone health; any conditions that may contraindicate X-ray exposure and no known current LSF, current lumbar bone stress or known unusual pathological changes (healed fractures, osteophytes, arthritic changes) to the lumbar spine which are known to affect BMD or BMC in the regions of interest. Rugby players were selected for comparison due to the known high bilateral lumbar spine BMD and BMC [21,22], while other cricketers were selected as it is likely they have a similar training volume to the fast bowlers.

2.3. Measurements

BMC and BMD were determined using dual X-ray absorptiometry (DXA) on a GE-Lunar Prodigy densitometer (GE, Madison, WI, USA). Lumbar spine scans were conducted in anteroposterior (AP) and lateral positions using standard positioning protocols, and whole vertebral (L1–L4) and lateral (L3) BMD (g/cm^2), BMC (g) and area (cm^2) were analysed (Lunar enCORE v17.0). Custom analysis of AP scans was used to split each vertebra into dominant (ipsilateral to bowling/throwing hand) and non-dominant sides of the lumbar spine. Rectangular custom regions of interest were added to the lateral 33% of each lumbar vertebral body, to exclude the mineral rich spinous process which can vary in their position, and BMD and BMC of these regions were calculated (Fig. 1A). To discriminate the vertebral body and posterior elements, a lateral scan was used. BMC, BMD and area of the L3 vertebral body and posterior elements was measured. The L3 vertebra was selected as L2 and L4 are often occluded by ribs or the pelvis, respectively. A custom region of interest was defined to include the whole vertebral body, with superior and inferior borders at the midpoint of the interventebral space. To include posterior elements, a further region of interest was defined with top and bottom borders parallel to the spinous process to include the entirety of the posterior elements (Fig. 1B). Repeatability of each analysis was determined using repeat scans in 20 participants on the same day with repositioning and demonstrated precision (RMS-SD, %CV) of L1–L4 BMD (0.006 g/cm^2, 0.41%) and BMC (1.308 g, 1.43%), lateral L3 vertebral body BMD (0.027 g/cm^2, 2.66%) and BMC (0.251 g, 2.15%), L3 posterior elements BMD (0.025 g/cm^2, 2.85%) and BMC (0.269 g, 2.50%), and all custom unilateral regions of interest BMD (0.024–0.035 g/cm^2, 1.79–2.42%) and BMC (0.182–0.271 g, 2.78–3.63%). Body fat percentage and fat free mass was determined from a whole body DXA scan. LSF history and unusual pathological changes was determined from England and Wales Cricket Board medical records with any diagnosis confirmed by MRI, CT or SPECT CT scans. A bone-specific physical activity questionnaire (BPAQ) was used to determine current, previous and total bone loading [31].

2.4. Statistical analysis

All statistical analyses were performed within SPSS v.23 (IBM, USA). One-way ANOVA determined if group or injury status differed in lumbar spine (L1–L4, lateral vertebral body or posterior element) BMD, BMC and area, with post-hoc Bonferonni correction determining differences between groups. Two-way mixed repeated measures ANOVA determined within and between group and between injury differences between dominant and non-dominant sides of the lumbar spine. A further one-way ANOVA was used if vertebral side had a significant interaction with group or injury, with a post-hoc Bonferonni correction to determine specific differences. Age and fat free mass were used as covariates to control for related changes in BMD and BMC in comparison between groups, while no covariates were used to compare within groups. If the assumption of normality was violated, a post-hoc Mann Whitney *U* test was used, with 0.05 divided by the number of tests being run to control for Type 1 error. Cohen's d (or r for non-parametric data) was calculated to determine the effect size of the difference between groups [32].
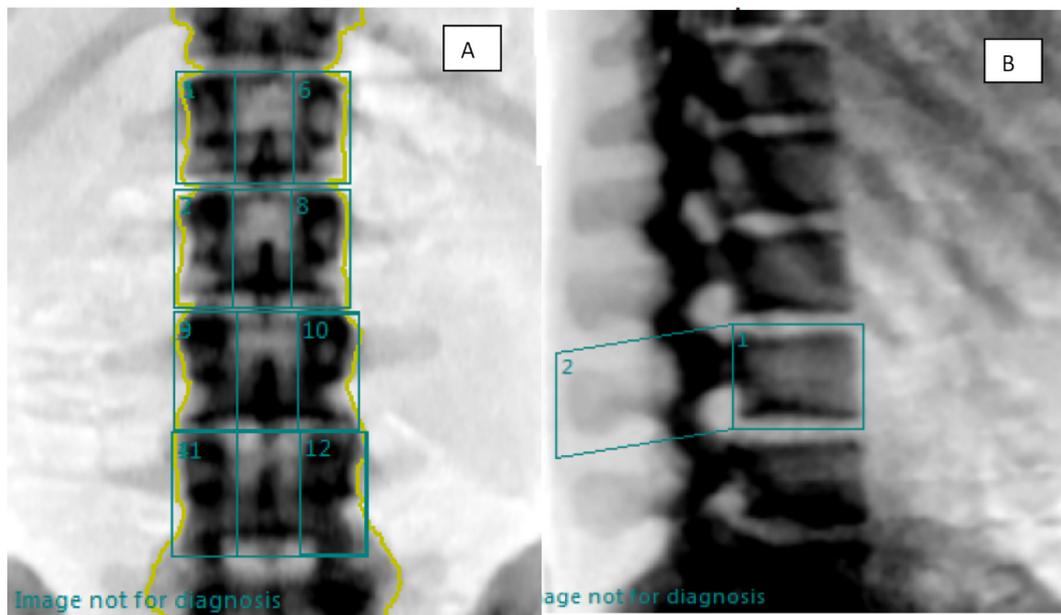
Fig. 1. Regions of interest used on the AP (A) and lateral (B) lumbar spine DXA scan.

3. Results

3.1. Participant characteristics and injury history

Of the 23 fast bowlers, 6 had a history of LSF and 7 had a history of lumbar disc injury. Of the 14 other cricketers, 5 had a history of lumbar disc injury. Characteristics of participants in each group can be found in Table 1.

3.2. Whole lumbar vertebrae

There was a significant effect of group on L1–L4: BMD, BMC, Z and T scores, and previous, current and total BPAQ ($P < 0.01$, $\eta\rho^2 = 0.37$–0.78), with significant differences between groups even after adjustment for fat free mass and age (Table 1). No significant effect of stress fracture or disc injury history was observed for age, height, body mass, any BPAQ, whole or lateral vertebra variable ($P > 0.05$, Supplementary File A).

3.3. Lumbar spine asymmetry (dominant v non-dominant)

BMD and BMC differed between vertebrae, and vertebral side in fast

bowlers ($P < 0.01$, $\eta\rho^2 = 0.40$–0.43) but not other groups, with greater BMD and BMC on the non-dominant side of the spine compared with the dominant side. The magnitude of BMD and BMC asymmetry increased with each vertebral level from L1 to L4 (BMD: 1.0%, 3.9%, 8.9% and 14.6%, BMC: 1.6%, 4.4%, 9.9% and 18.1% respectively). There was significant difference between sides at L4 ($P \leq 0.01$, $d = 0.98$–1.01, Figs. 2A and B). Differences between sides did not exceed 2.0% in BMD or 5.9% in BMC at any vertebral level in any of the other groups ($P > 0.05$).

3.4. L3 vertebral body and posterior element

L3 vertebral body and posterior element BMD were significantly greater in fast bowlers, other cricketers and rugby players compared with controls (17.4%–47.8%, $P \leq 0.02$, $d = 1.03$–1.78). L3 vertebral body BMC was significantly greater in both fast bowlers and rugby players compared with controls (26.1%–26.9%, $P \leq 0.03$, $d = 0.86$–0.96) but only fast bowlers had significantly greater BMC within the posterior elements than controls (33.3%, $P < 0.01$, $d = 1.20$, Table 2).

Table 1
Mean (SD) age, height, body mass, body fat, whole vertebral measures and previous bone loading of fast bowlers, other cricketers, rugby players and controls.

	Fast bowlers	Other cricketers	Rugby	Controls
Age (years)	24.58 (3.93)[b]	27.85 (3.73)[b,*]	21.27 (1.32)	21.56 (2.03)
Height (m)	1.88 (0.08)[*]	1.82 (0.06)	1.86 (0.07)[*]	1.79 (0.06)
Body mass (kg)	88.6 (9.85)[b,*]	82.7 (7.27)[b]	100.4 (11.06)[*]	76.8 (9.10)
Body fat %	15.9 (3.83)	16.0 (3.63)	17.2 (7.06)	20.6 (9.47)
Fat free mass (kg)	74.72 (8.37)[b,*]	69.87 (6.48)[b,*]	83.05 (7.88)[*]	60.71 (6.11)
L1–L4 BMD (g/cm^2)	1.56 (0.16)[*]	1.43 (0.13)[*]	1.47 (0.09)[*]	1.20 (0.13)
L1–L4 BMC (g)	114.49 (14.68)[a,b,*]	98.14 (9.90)[*]	107.02 (10.58)	79.06(12.35)
L1–L4 Area (mm^2)	73.57 (7.62)	68.75 (4.48)	72.76 (6.01)	65.52 (6.27)
L1–L4 Z-score	2.45 (1.24)[*]	1.57 (1.08)[*]	1.58 (0.85)[*]	−0.13 (1.08)
L1–L4 T-score	3.23 (1.38)[*]	2.07 (1.06)[*]	2.47 (0.78)[*]	0.26 (1.02)
Previous BPAQ	53.56 (36.24)[b]	35.00 (19.90)[b]	94.19 (26.86)[*]	39.81 (23.56)
Current BPAQ	6.21 (1.86)[b]	7.87 (1.93)[b]	21.09 (3.63)[*]	3.74 (5.70)
Total BPAQ	28.73 (18.62)[b]	22.58 (9.54)[b]	57.54 (13.46)[*]	21.72 (13.11)

[a] Significantly different to other cricketers.
[b] Significantly different to rugby.
[*] Significantly different to controls ($P < 0.05$). *Statistical tests between groups included fat free mass and age as covariates.*
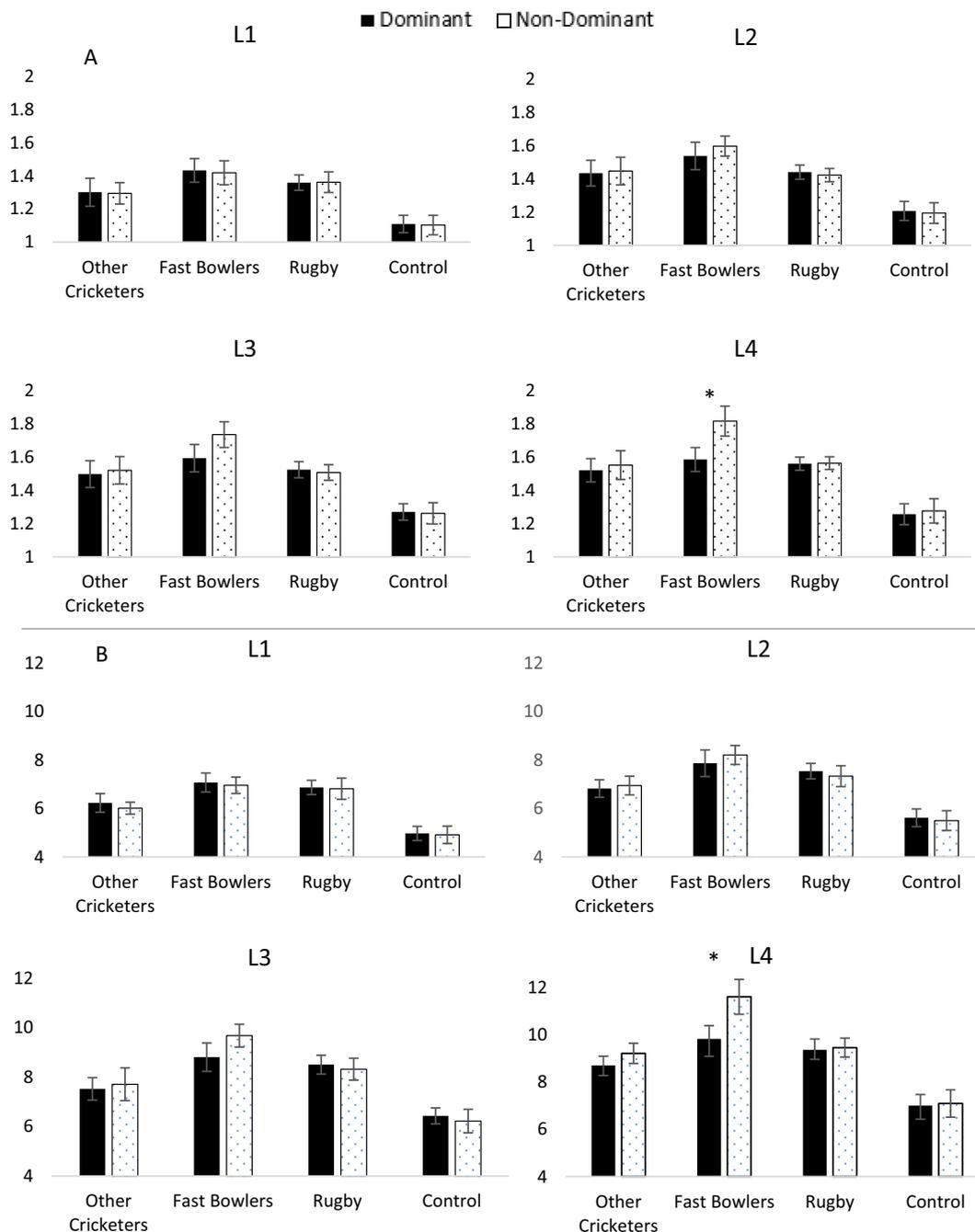
Fig. 2. Mean (± 95% CI) of (A) regional vertebra BMD (g/cm^2) and (B) regional vertebra BMC (g) between fast bowlers, other cricketers, rugby players and control participants. *denotes significantly ($P < 0.01$) different to ipsilateral side. *Covariates were not used in analysis within groups*.

3.5. Comparison of lumbar spine asymmetry between groups

There was a significant interaction between vertebra, side and group in BMD and BMC ($P < 0.01$, $\eta\rho^2 = 0.16$–0.17) even after adjustment for age and fat free mass. Analysis of dominant and non-dominant sides of the lumbar vertebrae demonstrated significant differences between groups in BMD and BMC ($P < 0.01$, $\eta\rho^2 = 0.27$–0.55, Fig. 2A and B). Significantly greater BMD and BMC was identified in

Table 2

Mean (SD) BMD (g/cm^2) and BMC (g) of L3 vertebral body and posterior elements in fast bowlers, other cricketers, rugby players and controls.

	Fast bowlers	Other cricketers	Rugby	Control
Vertebral body BMD	1.00 (0.11)*	0.98 (0.09)*	1.02 (0.13)*	0.77 (0.16)
Vertebral body BMC	13.73 (1.84)*	12.36 (1.53)	14.15 (2.14)*	9.78 (2.70)
Posterior elements BMD	1.10 (0.15)*	1.04 (0.12)*	0.98 (0.14)*	0.83 (0.14)
Posterior elements BMC	14.51 (2.17)*	13.10 (1.65)	13.23 (1.98)	10.28 (2.06)

* Significantly different to controls ($P < 0.05$). *Statistical tests between groups included fat free mass and age as covariates.*

fast bowlers compared to rugby players at the non-dominant L2, L3 and L4, (13.4%–33.3%, $P < 0.01$, d = 1.20–1.59) with no significant differences on the dominant side. Fast bowlers also had significantly greater BMD compared with other cricketers at the non-dominant L3 and L4 (13.3%–15.7%, $P < 0.01$, d = 1.00–1.03) with no differences on the dominant side, and significantly greater BMC at the non-dominant L2, L3 and L4 (13.5%–20.1%, $P < 0.05$, d = 0.91–1.01), and at the dominant L3 (14.8%, $P = 0.02$, d = 0.82). All active groups had significantly greater BMD in all custom areas of the lumbar spine compared with controls (17.1%–44.4%, $P < 0.05$, d = 1.15–1.83). Fast bowlers demonstrated significantly greater BMC at all custom areas compared with controls (24.3%–45.3%, $P < 0.01$, d = 0.98–1.46), other cricketers had significantly greater BMC at the non-dominant L2, L3 and L4 (19.9%–22.0%, $P < 0.05$, d = 1.02–1.17) and dominant L1 than controls (17.8%, $P = 0.02$, d = 1.04), and rugby players have significantly greater BMC at the dominant (18.2%, $P = 0.03$, d = 0.84) and non-dominant L1 than controls (20.1%, $P = 0.04$, d = 0.80). No significant differences were found between other cricketers and rugby players for any lumbar spine regional area ($P > 0.77$).

3.6. Lumbar asymmetry and injury

The interaction between side, vertebra and stress fracture status on BMD approached significance ($P = 0.08$), with the non-LSF fast bowlers demonstrating greater BMD on both dominant and non-dominant sides of the vertebra (3.6% and 1.7% respectively, Supplementary File A). No significant interaction was found between side, vertebra and stress fracture history on BMC ($P = 0.34$). There was no significant interaction between side, vertebra and disc injury history on BMD or BMC in fast bowlers ($P = 0.61$, $P = 0.77$) or other cricketers ($P = 0.28$, $P = 0.13$).

4. Discussion

The main new finding of this study is the site specific greater bone mass within the lumbar vertebra in response to a unilateral activity. Fast bowlers had greater BMD and BMC on the non-dominant side of the spine compared with the dominant side, specifically at L4 where BMD and BMC of the non-dominant side were significantly greater (14.6% and 18.1% respectively).

This site-specific adaptation can be further demonstrated by the comparison to rugby players, who had comparable whole L1–L4 BMD to cricketers. Fast bowlers had significantly higher BMD and BMC than rugby players at the non-dominant side L2, L3 and L4 (13.4%–33.3% greater) of the spine but not at the concurrent dominant side. A similar pattern was seen between fast bowlers and other cricketers with fast bowlers demonstrating significantly higher BMD at the non-dominant side L3 and L4 (13.3%–20.1%) and but no significant differences at the concurrent dominant side. While both fast bowlers and rugby players had significantly greater BMD and BMC in the lateral vertebral body compared to controls (26.1% - 29.4%), and greater BMD in the posterior elements (33.9% - 47.8%) only fast bowlers had significantly greater BMC in posterior elements compared with controls (33.27%). Fast bowlers thus had localised increases in BMD and BMC on the non-dominant side and in the posterior vertebral elements.

4.1. Activity specific adaptation

The extreme lumbar movements of fast bowling, which include contralateral side flexion, ipsilateral rotation and extension, occurring near simultaneously with each other [1] and with high vertical ground reaction forces [3], eliciting large compressive, torsional and shear forces upon the non-dominant side of the lumbar spine [5,33,34]. These forces may be transmitted to the lumbar spine via the musculature surrounding the lumbar spine, which attach to the posterior elements of the lumbar spine, and these forces are then transmitted from the

posterior elements to the vertebral body via the neural arch [35]. The neural arch is known to be highly adapted, with the pars interarticularis having the greatest amount of cortical bone within the posterior elements [36], while the pedicles have thick cylindrical walls with a hollow centre, both of which provide resistance to the strains placed upon these areas [35]. The forces involved during fast bowling are likely to put great bone strain upon these areas, triggering the modelling and remodelling response to reduce the strain upon the bone [6], possibly resulting in the site-specific bone mass increase seen in the non-dominant side and posterior elements of the fast bowlers lumbar spine in this study.

Cricket fast bowlers demonstrate unique asymmetric musculature of the lumbar spine which works in synergy in order to achieve stabilization of the spine and prevent injury [2]. The cross sectional area of the quadratus lumborum, multifidus and erector spinae were all significantly greater on the *dominant* side of the spine (4.5–7.2%, [2,37]), and attach to processes at the posterior elements on the same side of the vertebra. As the increments in BMD and BMC were seen at the *non-dominant* side, this may suggest that the action of these muscles may not be the major contributor to the bone adaptation observed in fast bowlers. The psoas major, however, has greater cross-sectional area on the non-dominant side of the lumbar spine (4.0%, [2,37]), and this side specific hypertrophy may drive the osteogenic response seen in the non-dominant side of the lumbar spine. Despite having minimal contribution to extension and flexion of the lumbar spine [35], it is known that the psoas major exerts large compressional loads upon the lower lumbar spine through its attachments on the transverse process of each lumbar vertebra [38]. It is known that elite fast bowlers demonstrate knee and hip extension during front foot contact, when vertical ground reaction forces are high [3], and which may attenuate this force into the lumbar spine via the psoas major, possibly contributing to the site specific adaptation observed in fast bowlers.

Previous research has demonstrated significantly greater BMD and BMC in the playing arm of male tennis and baseball players of up to 24% and 45% respectively [12–19], similar to the BMD increases, but much larger than the BMC increases observed on the non-dominant L4 in fast bowlers. It may be that the playing arm of the tennis or baseball players and the non-dominant side of the lumbar spine of the fast bowler have a similar magnitude of bone strain increase compared with the opposing side, resulting in a similar BMD response. Differences in BMC between cricket fast bowling, tennis and baseball may come from the weight bearing nature of the lumbar spine, thus reducing asymmetry. In comparison, the non-dominant arm of a tennis player is only required during two handed shots, while in baseball it is only required when batting. Differences in BMC may also arise from the type of loading required in each activity. To hit top spin ground strokes in tennis, or to throw a baseball, a large torsional force is produced in the playing arm by the muscles acting on the shoulder, elbow and wrist [13,39] which elicits an increase resistance to torsional forces through periosteal expansion, endosteal contraction, cortical mass and thickness [19,40]. It may be that the torsional forces sustained by the lumbar spine during fast bowling are less than those sustained by the playing arm of tennis or baseball players, but instead has a greater contribution of shear and compressive forces [5], which may be less osteogenic [41]. Further differences may arise from the shape of the bones, the bones in the arm are long bones, while the vertebra are irregular and may adapt in a different fashion to mechanical loading.

4.2. Site specific adaptation and injury

The stress fracture group had less bone mineral density on the dominant and non-dominant sides of the lumbar spine compared with control fast bowlers (3.6% and 1.7% respectively), although this was not significant ($P = 0.08$). The non-dominant pars interarticularis is the most common site for LSF in fast bowlers, and this may suggest that an inability to locally adapt sufficiently to the strain involved with fast

bowling may contribute to stress fracture. Alternatively the reduction in BMD may alternatively be a consequence of a previous stress fracture, which often have prolonged healing times [42]. Given the small number of stress fractures in this study this finding demonstrates the need to examine the aetiology of LSF in larger studies. Reduced bone mineral accrual may be affected by intrinsic factors such as maturity status, hormonal status, previous bone stress injury, bone geometry, muscular fatigue, vitamin D status and calcium homeostasis and extrinsic factors such as technique, workload, nutrition, cardiovascular fitness, muscle strength, endurance and flexibility, energy availability, pharmaceutic use and footwear [43–45].

4.3. Strengths and limitations

Strengths of this study are the unique cohort of elite cricket fast bowlers, who were scanned on the same DXA scanner. Limitations of this research are that as a cross-sectional study, it cannot demonstrate causality and cofounding variables such as prior injury could influence findings, although both players with stress fracture and those without demonstrated a similar asymmetric adaptation to fast bowling. Further, while it is possible that pathological changes could also cause this adaptation, this group of elite fast bowlers undergo regular screening and have a minimum of 1 MRI per year, so any pathological changes would have been noted and resulted in exclusion from the current study. A further limitation is the small number of stress fracture cases. With a larger cohort it may be possible to observe statistically significant changes in their regional BMD and BMC compared with fast bowlers who have not suffered stress fractures. Fast bowlers and other cricketers were significantly older than rugby players which may affect results as bone mass continues to increase until approximately 30 years, by age 19 however approximately 95–97% of total bone mineral and area has been accrued [46]. The sub-elite status of rugby players may have effected comparisons between groups as L1–L4 BMD are less than those found previously by 5% [22]. DXA provides a two-dimensional projection of a three-dimensional structure, which means the depth of bone cannot be directly measured, so DXA derived BMD is areal rather than volumetric [47], causing smaller bones to have a lower areal BMD than larger bones, even when volumetric BMD is the same [47–50]. The lateral scan of the lumbar spine uses a soft tissue reference region that may less accurately reflect the soft tissue overlying the bone, particularly for the posterior vertebral elements, affecting the attenuation characteristics and hence the estimated BMD and BMC [51]. However, soft tissue composition was similar between all the active groups, so this error should not invalidate comparisons between these groups.

4.4. Future research

Future research should investigate larger cohorts of LSF cases to determine if bone mineral accrual differs between LSF cases and controls, and prospective studies with baseline data taken pre-stress fracture are needed to determine if the lower BMD and BMC is causative or a consequence of stress fracture. Further research should explore the interaction between internal and external risk factors to LSF. Understanding the relationship between fast bowling technique, vertical ground reaction forces and regional bone mineral density and content will help determine which movements during fast bowling place the greatest strain upon the lumbar spine and could be used to inform safe adaptation of the lumbar spine to fast bowling.

4.5. Conclusion

Fast bowlers had localised increases in lumbar spine BMD and BMC, particularly on the non-dominant side and in the posterior vertebral elements. This study has demonstrated the remarkable ability of bone to respond within the lumbar vertebra to a high lumbar loading unilateral activity through site specific increases in bone mass. The ability of bone to respond to this loading may be implicated in the aetiology of lumbar stress fractures in fast bowlers.

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CRediT authorship contribution statement

Peter Alway: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Nicholas Peirce:**Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition, Data Curation, Formal Analysis. **Mark King:**Writing - review & editing, Visualization, Supervision, Methodology.**Robert Jardine:**Methodology, Data curation, Writing - review & editing, Investigation, Data Curation, Formal Analysis.**Katherine Brooke-Wavell:**Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

NP is an employee of the England and Wales Cricket Board.

References

[1] C.A. Ranson, A.F. Burnett, M. King, N. Patel, P.B. O'Sullivan, The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket, J. Sports Sci. 26 (2008) 267–276, https://doi.org/10.1080/02640410701501671.

[2] C. Ranson, A. Burnett, P. O'Sullivan, M. Batt, R. Kerslake, The lumbar paraspinal muscle morphometry of fast bowlers in cricket, Clin. J. Sport Med. 18 (2008) 31–37, https://doi.org/10.1097/JSM.0b013e3181618aa2.

[3] P. Worthington, M. King, C. Ranson, The influence of cricket fast bowlers' front leg technique on peak ground reaction forces, J. Sports Sci. 31 (2013) 434–441, https://doi.org/10.1080/02640414.2012.736628.

[4] J. Orchard, P. Blanch, J. Paoloni, A. Kountouris, K. Sims, P. Brukner, Cricket fast bowling workload patterns as risk factors for tendon, muscle, bone and joint injuries, Br. J. Sports Med. 49 (2015) 1064–1068, https://doi.org/10.1136/bjsports-2014-093683.

[5] H. Bayne, B. Elliott, A. Campbell, J. Alderson, Lumbar load in adolescent fast bowlers: a prospective injury study, J. Sci. Med. Sport 19 (2016) 117–122, https://doi.org/10.1016/j.jsams.2015.02.011.

[6] H.M. Frost, A 2003 update of bone physiology and Wolff's law for clinicians, Angle Orthod 74 (2004) 3–15, https://doi.org/10.1043/0003-3219(2004)074<0003:AUOBPA>2.0.CO;2.

[7] H.M. Frost, Bone "mass" and the "mechanostat": a proposal, Anat. Rec. 219 (1987) 1–9.

[8] H.M. Frost, Why do marathon runners have less bone than weight lifters? A vital-biomechanical view and explanation, Bone 20 (1997) 183–189, https://doi.org/10.1016/S8756-3282(96)00311-0.

[9] P. Christen, K. Ito, R. Ellouz, S. Boutroy, E. Sornay-Rendu, R.D. Chapurlat, B. Van Rietbergen, Bone remodelling in humans is load-driven but not lazy, Nat. Commun. 5 (2014) 1–5, https://doi.org/10.1038/ncomms5855.

[10] H.M. Frost, Bone's mechanostat: a 2003 update, Anat. Rec. Part a 275A (2003) 1081–1101, https://doi.org/10.1002/ar.a.10119.

[11] D.B. Burr, C. Millgrom, Musculoskeletal Fatigue and Stress Fractures, 1st ed, CRC Press, New York, 2000.

[12] J.A.L. Calbet, J.S. Moysi, C. Dorado, L.P. Rodriguez, Bone mineral content and density in professional tennis players, Calcif. Tissue Int. 62 (1998) 491–496, https://doi.org/10.1007/s002239900467.

[13] G. Ducher, D. Courteix, S. Même, C. Magni, J.F. Viala, C.L. Benhamou, Bone geometry in response to long-term tennis playing and its relationship with muscle volume: a quantitative magnetic resonance imaging study in tennis players, Bone 37 (2005) 457–466, https://doi.org/10.1016/j.bone.2005.05.014.

[14] G. Ducher, R.M. Daly, S.L. Bass, Effects of repetitive loading on bone mass and geometry in young male tennis players: a quantitative study using MRI, J. Bone Miner. Res. 24 (2009) 1686–1692, https://doi.org/10.1359/jbmr.090415.

[15] G. Ducher, N. Tournaire, A. Meddahi-Pellé, C.-L. Benhamou, D. Courteix, Short-term and long-term site-specific effects of tennis playing on trabecular and cortical bone at the distal radius, J. Bone Miner. Metab. 24 (2006) 484–490, https://doi.org/10.1007/s00774-006-0710-3.

[16] H. Haapasalo, S. Kontulainen, H. Sievanen, P. Kannus, M. Jarvinen, I. Vuori, Exercise-induced bone gain is due to enlargement in bone size without a change in volumetric bone density: a peripheral quantitative computed tomography study of the upper arms of male tennis players, Bone 27 (2000) 351–357.

[17] A. Ireland, T. Maden-Wilkinson, J. McPhee, K. Cooke, M. Narici, H. Degens, J. Rittweger, Upper limb muscle-bone asymmetries and bone adaptation in elite youth tennis players, Med. Sci. Sports Exerc. 45 (2013) 1749–1758, https://doi.org/10.1249/MSS.0b013e31828f882f.

[18] J. Sanchis-Moysi, C. Dorado, H. Olmedillas, J.A. Serrano-Sanchez, J.A.L. Calbet, Bone and lean mass inter-arm asymmetries in young male tennis players depend on training frequency, Eur. J. Appl. Physiol. 110 (2010) 83–90, https://doi.org/10.1007/s00421-010-1470-2.

[19] S.J. Warden, E.D. Bogenschutz, H.D. Smith, A.R. Gutierrez, Throwing induces substantial torsional adaptation within the midshaft humerus of male baseball players, Bone 45 (2009) 931–941, https://doi.org/10.1016/j.bone.2009.07.075.

[20] D.B. Burr, M.R. Forwood, D.P. Fyhrie, R.B. Martin, M.B. Schaffler, C.H. Turner, Bone microdamage and skeletal fragility in osteoporotic and stress fractures, J. Bone Miner. Res. 12 (1997) 6–15, https://doi.org/10.1359/jbmr.1997.12.1.6.

[21] M. Elloumi, O. Ben Ounis, D. Courteix, E. Makni, S. Sellami, Z. Tabka, G. Lac, Long-term rugby practice enhances bone mass and metabolism in relation with physical fitness and playing position, J. Bone Miner. Metab. 27 (2009) 713–720, https://doi.org/10.1007/s00774-009-0086-2.

[22] K. Hind, F. Birrell, B. Beck, Prevalent morphometric vertebral fractures in professional male rugby players, PLoS One 9 (2014) 5–10, https://doi.org/10.1371/journal.pone.0097427.

[23] P.D. Milburn, Biomechanics of Rugby union scrummaging, Sport. Med. 16 (1993) 168–179, https://doi.org/10.2165/00007256-199316030-00002.

[24] E. Seminati, D. Cazzola, E. Preatoni, G. Trewartha, Specific tackling situations affect the biomechanical demands experienced by rugby union players, Sport. Biomech. 16 (2017) 58–75, https://doi.org/10.1080/14763141.2016.1194453.

[25] L.K. Micklesfield, J. Gray, M.S. Taliep, Bone mineral density and body composition of South African cricketers, J. Bone Miner. Metab. 30 (2012) 232–237, https://doi.org/10.1007/s00774-011-0310-8.

[26] M. Johnson, M. Ferreira, J. Hush, Lumbar vertebral stress injuries in fast bowlers: a review of prevalence and risk factors, Phys. Ther. Sport 13 (2012) 45–52, https://doi.org/10.1016/j.ptsp.2011.01.002.

[27] P. Alway, K. Brooke-Wavell, B. Langley, M. King, N. Peirce, Incidence and prevalence of lumbar stress fracture in English County Cricket fast bowlers, association with bowling workload and seasonal variation, BMJ Open Sport Exerc. Med. 5 (2019) 1–7, https://doi.org/10.1136/bmjsem-2019-000529.

[28] H. De Visser, C. Adam, S. Crozier, M. Pearcy, The role of Quadratus Lumborum asymmetry in the occurrence of lesions in the lumbar vertebrae of cricket fast bowlers, Med. Eng. Phys. 29 (2007) 877–885.

[29] A. Nattiv, Stress fractures and bone health in track and field athletes, J. Sci. Med. Sport 3 (2000) 268–279, https://doi.org/10.1016/S1440-2440(00)80036-5.

[30] C.A. Ranson, R.W. Kerslake, A.F. Burnett, M.E. Batt, S. Abdi, Magnetic resonance imaging of the lumbar spine in asymptomatic professional fast bowlers in cricket, J. Bone Joint Surg. Br. 87 (2005) 1111–1116, https://doi.org/10.1302/0301-620X.87B8.16405.

[31] B.K. Weeks, B.R. Beck, The BPAQ: a bone-specific physical activity assessment instrument, Osteoporos. Int. 19 (2008) 1567–1577, https://doi.org/10.1007/s00198-008-0606-2.

[32] J. Cohen, Statistical Power Analysis for the Behvaioral Sciences, 2nd ed., Routledge, London, 1988.

[33] E. Chosa, K. Totoribe, N. Tajima, A biomechanical study of lumbar spondylolysis based on a three-dimensional finite element method, J. Orthop. Res. 22 (2004) 158–163, https://doi.org/10.1016/S0736-0266(03)00160-8.

[34] H. Crewe, A. Campbell, B. Elliott, J. Alderson, Lumbo-pelvic loading during fast bowling in adolescent cricketers: the influence of bowling speed and technique, J. Sports Sci. 31 (2013) 1082–1090, https://doi.org/10.1080/02640414.2012.762601.

[35] N. Bogduk, Clinical Anatomy of the Lumbar Spine and Sacrum, 3rd ed, Churchill Livingstone, New York, 1997.

[36] J. Krenz, J. Troup, The structure of the pars interarticularis of lower lumbar vertebrae and its relation to the etiology of spondylolysis, J. Bone Jt. Surg. 55B (1973) 735–741.

[37] J. Hides, W. Stanton, M. Freke, S. Wilson, S. McMahon, C. Richardson, Mri study of the size, symmetry and function of the trunk muscles among elite cricketers with and without low back pain, Br. J. Sports Med. 42 (2007) 809–813.

[38] N. Bogduk, M. Pearcy, G. Hadfield, Anatomy and biomechanics of psoas major, Clin. Biomech. 7 (1992) 109–119.

[39] M.B. Sabick, M.R. Torry, Y.K. Kim, R.J. Hawkins, Humeral torque in professional baseball pitchers, Am. J. Sports Med. 32 (2004) 892–898, https://doi.org/10.1177/0363546503259354.

[40] A. Ireland, H. Degens, N. Maffulli, J. Rittweger, Tennis service stroke benefits humerus bone: is torsion the cause? Calcif. Tissue Int. 97 (2015) 193–198, https://doi.org/10.1007/s00223-015-9995-3.

[41] I.J. Wallace, A.T. Kwaczala, S. Judex, B. Demes, K.J. Carlson, Physical activity engendering loads from diverse directions augments the growing skeleton, J. Musculoskelet. Neuronal Interact. 13 (2013) 245–250.

[42] L.J. Kidd, A.S. Stephens, J.S. Kuliwaba, N.L. Fazzalari, A.C.K. Wu, M.R. Forwood, Temporal pattern of gene expression and histology of stress fracture healing, Bone 46 (2010) 369–378, https://doi.org/10.1016/j.bone.2009.10.009.

[43] K. Bennell, G. Matheson, W. Meeuwisse, P. Brukner, Risk factors for stress fractures, Sport. Med. 28 (1999) 91–122, https://doi.org/10.2165/00007256-199928020-00004.

[44] S. Grimston, R. Zernicke, Exercise-related stress response bone review, J. Appl. Biomech. 9 (1993) 2–14.

[45] V.V. Välimäki, H. Alfthan, E. Lehmuskallio, E. Löyttyniemi, T. Sahi, H. Suominen, M.J. Välimäki, Risk factors for clinical stress fractures in male military recruits: a prospective cohort study, Bone 37 (2005) 267–273, https://doi.org/10.1016/j.bone.2005.04.016.

[46] A.D.G. Baxter-Jones, R.A. Faulkner, M.R. Forwood, R.L. Mirwald, D.A. Bailey, Bone mineral accrual from 8 to 30 years of age: an estimation of peak bone mass, J. Bone Miner. Res. 26 (2011) 1729–1739, https://doi.org/10.1002/jbmr.412.

[47] L.A. Binkovitz, M.J. Henwood, Pediatric DXA: technique and interpretation, Pediatr. Radiol. 37 (2007) 21–31, https://doi.org/10.1007/s00247-006-0153-y.

[48] L. Bachrach, Editorial: osteoporosis in children: still a diagnostic challenge, J. Clin. Endocrinol. Metab. 92 (2007) 2030–2032, https://doi.org/10.1210/jc.2007-0828.

[49] G.A. Kline, D.A. Hanley, Differences of vertebral area in serial bone density measurements: a common source of potential error in interpretation of BMD change, J. Clin. Densitom. 9 (2006) 419–424, https://doi.org/10.1016/j.jocd.2006.08.006.

[50] B.L. Specker, E. Schoenau, Quantitative bone analysis in children: current methods and recommendations, J. Pediatr. 146 (2005) 726–731, https://doi.org/10.1016/j.jpeds.2005.02.002.

[51] P. Tothill, D.W. Pye, Errors due to non-uniform distribution of fat in dual X-ray absorptiometry of the lumbar spine, Br. J. Radiol. 65 (1992) 807–813, https://doi.org/10.1259/0007-1285-65-777-807.