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2 **Lumbar bone mineral asymmetry in elite cricket fast bowlers**

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21

22 **ABSTRACT**

23 **Purpose**

24 Bone responds to mechanical loading by increasing bone mineral density (BMD) and/or bone
25 area to enhance bone strength at the site of the greatest strain. Such localised adaptation has
26 not been demonstrated at the spine. The aim of this study is to determine if BMD and/or bone
27 mineral content (BMC) differs between dominant (ipsilateral to bowling/throwing arm) and
28 non-dominant sides of the vertebrae in cricket fast bowlers, and whether this asymmetry
29 differs according to stress fracture or disc injury history. A further aim was to determine if
30 regional BMD and BMC in the lumbar spine differ between fast bowlers, other cricketers,
31 rugby players and non-active controls, to highlight the site-specific response of lumbar
32 vertebra to unilateral activity

33 **Methods**

34 23 fast bowlers, 14 other cricketers, 22 rugby players and 20 controls underwent an antero-
35 posterior (AP) and lateral DXA scans of their lumbar spine to assess BMD, BMC and area. A
36 custom analysis measured BMD and BMC of the dominant and non-dominant sides (lateral
37 33%) of the AP lumbar spine. BMD and BMC were compared between groups, injury status,
38 vertebrae and sides using ANOVA.

39 **Results**

40 Analysis of medical records showed that 6 fast bowlers had a history of lumbar stress fracture.
41 Significantly greater BMD and BMC was found in the L4 non-dominant vertebra compared
42 with the dominant vertebra in fast bowlers. BMD and BMC differed significantly according to
43 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.

Keywords: cricket; bone mineral; physical activity; mechanostat; lumbar stress fracture.

Abbreviations: Bone mineral density (BMD), Bone mineral content (BMC), Lumbar stress fracture (LSF)

64 1. Introduction

65 Cricket fast bowling is a unique unilateral movement pattern defined by extreme multi-planar
66 trunk movements greater than 125% of active range of motion (Ranson et al., 2008), high
67 vertical ground reaction forces in excess of 7 times body weight at front foot contact
68 (Worthington et al., 2013) and high match workloads greater than 2400 deliveries in a season
69 (Orchard et al., 2015), contributing to a large lumbar load, where peak lumbar forces can
70 exceed 20 N/kg^{-1} and peak lumbo-pelvic moments can exceed of $10 \text{ Nm/kg}^{-1}/\text{m}^{-1}$ per delivery
71 in all three directions (Bayne et al., 2016).

72 Bone is a remarkable material capable of responding to its mechanical environment to
73 balance the efficiency of locomotion with strength of the bone (Frost, 2004). This response
74 may be governed by a 'mechanostat' (Frost, 1987) which optimises mass and architecture of
75 bone through modelling (Frost, 1997) and remodelling (Christen et al., 2014) processes to
76 ensure that typical local peak bone strains are minimized to keep strains below the
77 microdamage threshold, preventing acute or fatigue fractures (Frost, 2003). Where typical
78 peak mechanical strains exceed the microdamage threshold, microdamage can escape usual
79 repair, accumulating and coalescing, increasing fragility and increasing the risk of sustaining a
80 stress fracture (Burr and Millgrom, 2000).

81 Site-specific response of bone to a stressful mechanical environment can be observed in male
82 tennis and baseball players, whose playing arms demonstrate significantly greater BMD and
83 BMC of up to 24% and 45% respectively compared with their non-playing arms (Calbet et al.,
84 1998; Ducher et al., 2009, 2006, 2005; Haapasalo et al., 2000; Ireland et al., 2013; Sanchis-
85 Moysi et al., 2010; Warden et al., 2009) This response was suggested to be due to the
86 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 (Burr et al., 1997). 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 (Elloumi et al., 2009; Hind et al., 2014) in response to the high bilateral forces sustained by the trunk during collisions, tackling and while scrummaging (Milburn, 1993; Seminati et al., 2017).

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 (Micklesfield et al., 2012). 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 (Johnson et al., 2012). LSF are most prevalent at the fourth and fifth lumbar vertebra (66% of all incidence), with 93% of all LSF occurring at the neural arch on the non-dominant side (contralateral to bowling arm, Alway et al., 2019). 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 (De Visser et al., 2007). 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 (Nattiv, 2000). Another common injury in fast bowlers are injuries to the intervertebral discs of the lumbar

109 spine, with up to 61% of fast bowlers demonstrating abnormalities on MRI (Ranson et al.,
110 2005).

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

117

118 **2. Methods**

119 **2.1 Experimental Design**

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

125 **2.2 Participants**

126 Participants included 37 elite male cricketers (23 fast bowlers, 14 other cricketers (11 batters,
127 2 wicketkeepers, 1 spin bowler), 22 rugby players and 20 control participants. Inclusion
128 criteria for the cricketers were participation in national senior or developmental squads. Fast
129 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 (Elloumi et al., 2009; Hind et al., 2014), 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 (Figure 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 intervertebral 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 (Figure 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 ($0.024 - 0.035 \text{ g/cm}^2$, 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 (Weeks and Beck, 2008).

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 (Cohen, 1988).

*****Figure 1 goes around here *****

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.

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)‡	27.85 (3.73)‡*	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)‡*	82.7 (7.27)‡	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)‡*	69.87 (6.48)‡*	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)†‡*	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)‡	35.00 (19.90)‡	94.19 (26.86)*	39.81 (23.56)
Current BPAQ	6.21 (1.86)‡	7.87 (1.93)‡	21.09 (3.63)*	3.74 (5.70)
Total BPAQ	28.73 (18.62)‡	22.58 (9.54)‡	57.54 (13.46)*	21.72 (13.11)

† significantly different to other cricketers, ‡ significantly different to rugby, * significantly different to controls ($P < 0.05$). Statistical tests between groups included fat free mass and age as covariates.

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 ($P < 0.01$, $\eta^2 = 0.37 - 0.78$), 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 ($p < 0.01$, $\eta p^2 = 0.40 - 0.43$) 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 ($P \leq 0.01$, $d = 0.98 - 1.01$, Figures 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 2: Mean (SD) BMD (g/cm²) 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.

3.5 Comparison of lumbar spine asymmetry between groups

There was a significant interaction between vertebra, side and group in BMD and BMC ($P < 0.01$, $\eta^2 = 0.16$ - 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 ($P < 0.01$, $\eta^2 = 0.27 - 0.55$, Figures 2A and 2B). Significantly greater BMD and BMC was identified in 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 ($P = 0.28$, $P = 0.13$).

***** Figure 2 goes around here *****

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 (Ranson et al., 2008) and with high vertical ground reaction forces (Worthington et al., 2013), eliciting

283 large compressive, torsional and shear forces upon the non-dominant side of the lumbar
284 spine (Bayne et al., 2016; Chosa et al., 2004; Crewe et al., 2013). These forces may be
285 transmitted to the lumbar spine via the musculature surrounding the lumbar spine, which
286 attach to the posterior elements of the lumbar spine, and these forces are then transmitted
287 from the posterior elements to the vertebral body via the neural arch (Bogduk, 1997). The
288 neural arch is known to be highly adapted, with the pars interarticularis having the greatest
289 amount of cortical bone within the posterior elements (Krenz and Troup, 1973), while the
290 pedicles have thick cylindrical walls with a hollow centre, both of which provide resistance to
291 the strains placed upon these areas (Bogduk, 1997). The forces involved during fast bowling
292 are likely to put great bone strain upon these areas, triggering the modelling and remodelling
293 response to reduce the strain upon the bone (Frost, 2004), possibly resulting in the site-
294 specific bone mass increase seen in the non-dominant side and posterior elements of the fast
295 bowlers lumbar spine in this study.

296 Cricket fast bowlers demonstrate unique asymmetric musculature of the lumbar spine which
297 works in synergy in order to achieve stabilization of the spine and prevent injury (Ranson et
298 al. 2008). The cross sectional area of the quadratus lumborum, multifidus and erector spinae
299 were all significantly greater on the *dominant* side of the spine (4.5 – 7.2%, Hides et al., 2007;
300 Ranson et al., 2008), and attach to processes at the posterior elements on the same side of
301 the vertebra. As the increments in BMD and BMC were seen at the *non-dominant* side, this
302 may suggest that the action of these muscles may not be the major contributor to the bone
303 adaptation observed in fast bowlers. The psoas major, however, has greater cross-sectional
304 area on the non-dominant side of the lumbar spine (4.0%, Hides et al., 2007; Ranson et al.,
305 2008), 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 (Bogduk, 1997), 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 (Bogduk et al., 1992). It is known that elite fast bowlers demonstrate knee and hip extension during front foot contact, when vertical ground reaction forces are high (Worthington et al., 2013), 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 (Calbet et al., 1998; Ducher et al., 2009, 2006, 2005; Haapasalo et al., 2000; Ireland et al., 2013; Sanchis-Moysi et al., 2010; Warden et al., 2009), 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 (Ducher et al., 2005; Sabick et al., 2004) which elicits an increase resistance to torsional forces through periosteal expansion,

endosteal contraction, cortical mass and thickness (Ireland et al., 2015; Warden et al., 2009). 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 (Bayne et al., 2016), which may be less osteogenic (Wallace et al., 2013). 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 (Kidd et al., 2010). 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, pharmaceutical use and footwear (Bennell et al., 1999; Grimston and Zernicke, 1993; Välimäki et al., 2005).

4.3 Strengths and Limitations

352 Strengths of this study are the unique cohort of elite cricket fast bowlers, who were scanned
353 on the same DXA scanner. Limitations of this research are that as a cross-sectional study, it
354 cannot demonstrate causality and confounding variables such as prior injury could influence
355 findings, although both players with stress fracture and those without demonstrated a similar
356 asymmetric adaptation to fast bowling. Further, while it is possible that pathological changes
357 could also cause this adaptation, this group of elite fast bowlers undergo regular screening
358 and have a minimum of 1 MRI per year, so any pathological changes would have been noted
359 and resulted in exclusion from the current study. A further limitation is the small number of
360 stress fracture cases. With a larger cohort it may be possible to observe statistically significant
361 changes in their regional BMD and BMC compared with fast bowlers who have not suffered
362 stress fractures. Fast bowlers and other cricketers were significantly older than rugby players
363 which may affect results as bone mass continues to increase until approximately 30 years, by
364 age 19 however approximately 95-97% of total bone mineral and area has been accrued
365 (Baxter-Jones et al., 2011). The sub-elite status of rugby players may have effected
366 comparisons between groups as L1-L4 BMD are less than those found previously by 5% (Hind
367 et al. 2014). DXA provides a two-dimensional projection of a three-dimensional structure,
368 which means the depth of bone cannot be directly measured, so DXA derived BMD is areal
369 rather than volumetric (Binkovitz and Henwood, 2007), causing smaller bones to have a lower
370 areal BMD than larger bones, even when volumetric BMD is the same (Bachrach, 2007;
371 Binkovitz and Henwood, 2007; Kline and Hanley, 2006; Specker and Schoenau, 2005). The
372 lateral scan of the lumbar spine uses a soft tissue reference region that may less accurately
373 reflect the soft tissue overlying the bone, particularly for the posterior vertebral elements,
374 affecting the attenuation characteristics and hence the estimated BMD and BMC (Tothill and

Pye, 1992). 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.

396 **5. REFERENCES**

- 397 Alway, P., Brooke-Wavell, K., Langley, B., King, M., Peirce, N., 2019. Incidence and
398 prevalence of lumbar stress fracture in English County Cricket fast bowlers, association
399 with bowling workload and seasonal variation. *BMJ Open Sport Exerc. Med.* 5, 1–7.
400 <https://doi.org/10.1136/bmjsem-2019-000529>
- 401 Bachrach, L., 2007. Editorial: Osteoporosis in Children: Still a Diagnostic Challenge. *J. Clin.*
402 *Endocrinol. Metab.* 92, 2030–2032. <https://doi.org/10.1210/jc.2007-0828>
- 403 Baxter-Jones, A.D.G., Faulkner, R.A., Forwood, M.R., Mirwald, R.L., Bailey, D.A., 2011. Bone
404 mineral accrual from 8 to 30 years of age: An estimation of peak bone mass. *J. Bone*
405 *Miner. Res.* 26, 1729–1739. <https://doi.org/10.1002/jbmr.412>
- 406 Bayne, H., Elliott, B., Campbell, A., Alderson, J., 2016. Lumbar load in adolescent fast
407 bowlers: A prospective injury study. *J. Sci. Med. Sport* 19, 117–122.
408 <https://doi.org/10.1016/j.jsams.2015.02.011>
- 409 Bennell, K., Matheson, G., Meeuwisse, W., Brukner, P., 1999. Risk Factors for Stress
410 Fractures. *Sport. Med.* 28, 91–122. [https://doi.org/10.2165/00007256-199928020-](https://doi.org/10.2165/00007256-199928020-00004)
411 [00004](https://doi.org/10.2165/00007256-199928020-00004)
- 412 Binkovitz, L.A., Henwood, M.J., 2007. Pediatric DXA: Technique and interpretation. *Pediatr.*
413 *Radiol.* 37, 21–31. <https://doi.org/10.1007/s00247-006-0153-y>
- 414 Bogduk, N., 1997. *Clinical Anatomy of the Lumbar Spine and Sacrum*, 3rd ed. Churchill
415 Livingstone, New York.
- 416 Bogduk, N., Pearcy, M., Hadfield, G., 1992. Anatomy and biomechanics of psoas major. *Clin.*

417 Biomech. 7, 109–119.

418 Burr, D.B., Forwood, M.R., Fyhrie, D.P., Martin, R.B., Schaffler, M.B., Turner, C.H., 1997.

419 Bone Microdamage and Skeletal Fragility in Osteoporotic and Stress Fractures. J. Bone

420 Miner. Res. 12, 6–15. <https://doi.org/10.1359/jbmr.1997.12.1.6>

421 Burr, D.B., Millgrom, C., 2000. Musculoskeletal Fatigue and Stress Fractures, 1st ed. CRC

422 Press, New York.

423 Calbet, J.A.L., Moysi, J.S., Dorado, C., Rodriguez, L.P., 1998. Bone mineral content and

424 density in professional tennis players. Calcif. Tissue Int. 62, 491–496.

425 <https://doi.org/10.1007/s002239900467>

426 Chosa, E., Totoribe, K., Tajima, N., 2004. A biomechanical study of lumbar spondylolysis

427 based on a three-dimensional finite element method. J. Orthop. Res. 22, 158–163.

428 [https://doi.org/10.1016/S0736-0266\(03\)00160-8](https://doi.org/10.1016/S0736-0266(03)00160-8)

429 Christen, P., Ito, K., Ellouz, R., Boutroy, S., Sornay-Rendu, E., Chapurlat, R.D., Van Rietbergen,

430 B., 2014. Bone remodelling in humans is load-driven but not lazy. Nat. Commun. 5, 1–5.

431 <https://doi.org/10.1038/ncomms5855>

432 Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, 2nd ed. Routledge,

433 London.

434 Crewe, H., Campbell, A., Elliott, B., Alderson, J., 2013. Lumbo-pelvic loading during fast

435 bowling in adolescent cricketers: The influence of bowling speed and technique. J.

436 Sports Sci. 31, 1082–1090. <https://doi.org/10.1080/02640414.2012.762601>

437 De Visser, H., Adam, C., Crozier, S., Pearcy, M., 2007. The role of Quadratus Lumborum

438 asymmetry in the occurrence of lesions in the lumbar vertebrae of cricket fast bowlers.
 439 Med. Eng. Phys. 29, 877–885.

440 Ducher, G., Courteix, D., Môme, S., Magni, C., Viala, J.F., Benhamou, C.L., 2005. Bone
 441 geometry in response to long-term tennis playing and its relationship with muscle
 442 volume: A quantitative magnetic resonance imaging study in tennis players. Bone 37,
 443 457–466. <https://doi.org/10.1016/j.bone.2005.05.014>

444 Ducher, G., Daly, R.M., Bass, S.L., 2009. Effects of repetitive loading on bone mass and
 445 geometry in young male tennis players: A quantitative study using MRI. J. Bone Miner.
 446 Res. 24, 1686–1692. <https://doi.org/10.1359/jbmr.090415>

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

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

455 Frost, H.M., 2004. A 2003 update of bone physiology and Wolff’s Law for Clinicians. Angle
 456 Orthod. 74, 3–15. [https://doi.org/10.1043/0003-](https://doi.org/10.1043/0003-3219(2004)074<0003:AUOBPA>2.0.CO;2)
 457 [3219\(2004\)074<0003:AUOBPA>2.0.CO;2](https://doi.org/10.1043/0003-3219(2004)074<0003:AUOBPA>2.0.CO;2)

458 Frost, H.M., 2003. Bone’s mechanostat: A 2003 update. Anat. Rec. Part a 275A, 1081–1101.
 459 <https://doi.org/10.1002/ar.a.10119>

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

463 Frost, H.M., 1987. Bone “ Mass ” and the “ Mechanostat ”: A Proposal. *Anat. Rec.* 219, 1–9.

464 Grimston, S., Zernicke, R., 1993. Exercise-related stress response bone review. *J. Appl.*
 465 *Biomech.* 9, 2–14.

466 Haapasalo, H., Kontulainen, S., Sievanen, H., Kannus, P., Jarvinen, M., Vuori, I., 2000.
 467 Exercise-induced Bone Gain Is Due to Enlargement in Bone Size Without a Change in
 468 Volumetric Bone Density: A Peripheral Quantitative Computed Tomography Study of
 469 the Upper Arms of Male Tennis Players. *Bone* 27, 351–357.

470 Hides, J., Stanton, W., Freke, M., Wilson, S., McMahon, S., Richardson, C., 2007. Mri Study of
 471 the Size , Symmetry and Function of the Trunk muscles among elite cricketers with and
 472 without low back pain. *Br. J. Sports Med.* 42, 809–813.

473 Hind, K., Birrell, F., Beck, B., 2014. Prevalent morphometric vertebral fractures in
 474 professional male rugby players. *PLoS One* 9, 5–10.
 475 <https://doi.org/10.1371/journal.pone.0097427>

476 Ireland, A., Degens, H., Maffulli, N., Rittweger, J., 2015. Tennis service stroke benefits
 477 humerus bone: Is torsion the cause? *Calcif. Tissue Int.* 97, 193–198.
 478 <https://doi.org/10.1007/s00223-015-9995-3>

479 Ireland, A., Maden-Wilkinson, T., McPhee, J., Cooke, K., Narici, M., Degens, H., Rittweger, J.,
 480 2013. Upper limb muscle-bone asymmetries and bone adaptation in elite youth tennis

481 players. *Med. Sci. Sports Exerc.* 45, 1749–1758.

482 <https://doi.org/10.1249/MSS.0b013e31828f882f>

483 Johnson, M., Ferreira, M., Hush, J., 2012. Lumbar vertebral stress injuries in fast bowlers: A

484 review of prevalence and risk factors. *Phys. Ther. Sport* 13, 45–52.

485 <https://doi.org/10.1016/j.ptsp.2011.01.002>

486 Kidd, L.J., Stephens, A.S., Kuliwaba, J.S., Fazzalari, N.L., Wu, A.C.K., Forwood, M.R., 2010.

487 Temporal pattern of gene expression and histology of stress fracture healing. *Bone* 46,

488 369–378. <https://doi.org/10.1016/j.bone.2009.10.009>

489 Kline, G.A., Hanley, D.A., 2006. Differences of Vertebral Area in Serial Bone Density

490 Measurements: A Common Source of Potential Error in Interpretation of BMD Change.

491 *J. Clin. Densitom.* 9, 419–424. <https://doi.org/10.1016/j.jocd.2006.08.006>

492 Krenz, J., Troup, J., 1973. The structure of the pars interarticularis of lower lumbar vertebrae

493 and its relation to the etiology of spondylolysis. *J. Bone Jt. Surg.* 55B, 735–741.

494 Micklesfield, L.K., Gray, J., Taliep, M.S., 2012. Bone mineral density and body composition of

495 South African cricketers. *J. Bone Miner. Metab.* 30, 232–237.

496 <https://doi.org/10.1007/s00774-011-0310-8>

497 Milburn, P.D., 2009. Biomechanics of Rugby Union Scrummaging. *Sport. Med.* 16, 168–179.

498 <https://doi.org/10.2165/00007256-199316030-00002>

499 Nattiv, A., 2000. Stress fractures and bone health in track and field athletes. *J. Sci. Med.*

500 *Sport* 3, 268–279. [https://doi.org/10.1016/S1440-2440\(00\)80036-5](https://doi.org/10.1016/S1440-2440(00)80036-5)

501 Orchard, J., Blanch, P., Paoloni, J., Kountouris, A., Sims, K., Brukner, P., 2015. Cricket fast

502 bowling workload patterns as risk factors for tendon, muscle, bone and joint injuries.
503 Br. J. Sports Med. 49, 1064–8. <https://doi.org/10.1136/bjsports-2014-093683>

504 Ranson, C.A., Burnett, A.F., King, M., Patel, N., O’Sullivan, P.B., 2008. The relationship
505 between bowling action classification and three-dimensional lower trunk motion in fast
506 bowlers in cricket. J. Sports Sci. 26, 267–276.
507 <https://doi.org/10.1080/02640410701501671>

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

511 Ranson, C., Burnett, A., O’Sullivan, P., Batt, M., Kerslake, R., 2008. The Lumbar Paraspinal
512 Muscle Morphometry of Fast Bowlers in Cricket. Clin. J. Sport Med. 18, 31–37.
513 <https://doi.org/10.1097/JSM.0b013e3181618aa2>

514 Sabick, M.B., Torry, M.R., Kim, Y.K., Hawkins, R.J., 2004. Humeral torque in professional
515 baseball pitchers. Am. J. Sports Med. 32, 892–898.
516 <https://doi.org/10.1177/0363546503259354>

517 Sanchis-Moysi, J., Dorado, C., Olmedillas, H., Serrano-Sanchez, J.A., Calbet, J.A.L., 2010. Bone
518 and lean mass inter-arm asymmetries in young male tennis players depend on training
519 frequency. Eur. J. Appl. Physiol. 110, 83–90. [https://doi.org/10.1007/s00421-010-1470-](https://doi.org/10.1007/s00421-010-1470-2)
520 2

521 Seminati, E., Cazzola, D., Preatoni, E., Trewartha, G., 2017. Specific tackling situations affect
522 the biomechanical demands experienced by rugby union players. Sport. Biomech. 16,
523 58–75. <https://doi.org/10.1080/14763141.2016.1194453>

524 Specker, B.L., Schoenau, E., 2005. Quantitative bone analysis in children: Current methods
525 and recommendations. *J. Pediatr.* 146, 726–731.
526 <https://doi.org/10.1016/j.jpeds.2005.02.002>

527 Tothill, P., Pye, D.W., 1992. Errors due to non-uniform distribution of fat in dual X-ray
528 absorptiometry of the lumbar spine. *Br. J. Radiol.* 65, 807–813.
529 <https://doi.org/10.1259/0007-1285-65-777-807>

530 Välimäki, V.V., Alfthan, H., Lehmuskallio, E., Löyttyniemi, E., Sahi, T., Suominen, H., Välimäki,
531 M.J., 2005. Risk factors for clinical stress fractures in male military recruits: A
532 prospective cohort study. *Bone* 37, 267–273.
533 <https://doi.org/10.1016/j.bone.2005.04.016>

534 Wallace, I.J., Kwaczala, A.T., Judex, S., Demes, B., Carlson, K.J., 2013. Physical activity
535 engendering loads from diverse directions augments the growing skeleton. *J.*
536 *Musculoskelet. Neuronal Interact.* 13, 245–250.

537 Warden, S.J., Bogenschutz, E.D., Smith, H.D., Gutierrez, A.R., 2009. Throwing induces
538 substantial torsional adaptation within the midshaft humerus of male baseball players.
539 *Bone* 45, 931–941. <https://doi.org/10.1016/j.bone.2009.07.075>

540 Weeks, B.K., Beck, B.R., 2008. The BPAQ: A bone-specific physical activity assessment
541 instrument. *Osteoporos. Int.* 19, 1567–1577. [https://doi.org/10.1007/s00198-008-](https://doi.org/10.1007/s00198-008-0606-2)
542 [0606-2](https://doi.org/10.1007/s00198-008-0606-2)

543 Worthington, P., King, M., Ranson, C., 2013. The influence of cricket fast bowlers' front leg
544 technique on peak ground reaction forces. *J. Sports Sci.* 31, 434–441.
545 <https://doi.org/10.1080/02640414.2012.736628>

Figure 1: Regions of interest used on the AP (A) and lateral (B) lumbar spine DXA scan

Figure 2: Mean ($\pm$ 95% CI) of (A) regional vertebra BMD (g/cm²) and (B) regional vertebra BMC 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.*

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Highlights

- Cricket fast bowlers have greater BMD and BMC at the non-dominant (contralateral to bowling arm) side of the AP lumbar spine
- This asymmetry increases in magnitude caudally, significantly differing to the dominant side at L4.
- Fast bowlers have significantly greater bone mineral than rugby players at the non-dominant side of L2, L3 and L4, but not the dominant side
- Reduced site-specific bone mineral accrual may be a risk factor to lumbar stress fracture in fast bowlers