Bone density and cross-sectional geometry of the proximal femur are bilaterally elevated in elite cricket fast bowlers

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Abstract

The skeleton of a cricket fast bowler is exposed to a unique combination of gravitational and torsional loading in the form of substantial ground reaction forces delivered through the front landing foot, and anterior-posterior shear forces mediated by regional muscle contractions across the lumbo-pelvic region. The objectives of this study were to compare the hip structural characteristics of elite fast bowlers with recreationally-active age-matched controls, and to examine unilateral bone properties in fast bowlers. Dual-energy X-ray absorptiometry (DXA) of the proximal femur was performed in 26 elite male fast bowlers and 26 normally-active controls. Hip structural analysis (GE Lunar; enCORE version 15.0) determined areal bone mineral density (BMD) of the proximal femur, and cross-sectional area (CSA), section modulus (Z), cross-sectional moment of inertia (CSMI) and femoral strength index (FSI) at the narrow region of the femoral neck. Mean femoral neck and trochanter BMD were greater in fast bowlers than controls ($p<0.001$). All bone geometry properties except for CSMI were superior in fast bowlers ($p<0.05$) following adjustment for height and lean mass. There were no asymmetries in BMD or bone geometry when considering leg dominance of the fast bowlers ($p>0.05$). Elite fast bowlers have superior bone characteristics of the proximal femur, with results inferring enhanced resistance to axial compression (CSA), and bending (Z) forces, and enhanced strength to withstand a fall impact as indicated by their higher FSI. No asymmetries in hip bone properties were identified, suggesting that both torsional and gravitational loading offer significant osteogenic potential.

Keywords: DXA, cricket, fast bowling, loading, imaging, team sport

Introduction

Bone adapts architecturally to reflect its habitual loading environment [1] and responds to a wide range of biochemical and physical stimuli [1, 2]. In particular, the musculoskeletal loading sustained during exercise serves as a major osteogenic stimulus [3] that is essential for the development of a functionally and mechanically appropriate skeleton, the attainment of optimal peak bone mass, and the subsequent maintenance of bone strength as a prophylaxis against osteoporosis [4, 5]. This phenomenon is comprehensively described in the Mechanostat theory [6], which proposes that when all else is equal, individuals that are physically active should possess stronger bones than their less active peers.

The osteogenic response to loading is site-specific and is reflected through differences in bone mass and size between the dominant and non-dominant limbs [7, 8], and site-specific bone loss during unilateral limb immobilisation [9]. To date, a large number of studies have demonstrated the effectiveness of gravitational loading in stimulating bone anabolic responses in various regions of the hip over an individual's lifespan [4, 10]. This is important because the hip, and in particular the femoral neck, is the site at which osteoporotic fractures are most devastating and costly [11]. It has been proposed that regional muscle forces offer the greatest mechano-stimulus to bone [12], with studies building on early evidence provided by Rubin et al. [13] that torsional loading is a more compelling anabolic stimulus than axial loading in disuse-related bone loss.

The skeletal loading generated through playing cricket appears to be beneficial for bone density at the hip [14] and in particular, fast bowlers appear to be exposed to a unique loading environment that is worthy of investigation. Substantial ground reaction forces are transmitted through the landing foot, representing axial gravitational loading, and torsional loading is generated through peak transverse plane rotation moments and anterior-posterior shear forces across the lumbo-pelvic region [15, 16]. A typical fast bowling delivery is initiated with a run-up to the wicket, culminating in the delivery stride or bowling action, and ending in the follow-through [17, 18]. Sequentially, the delivery stride comprises the back foot contact, front foot contact and ball release phases [18]. At front foot contact, bowlers absorb ground reaction forces of between 3.8 and 9.0 times body mass [15, 17, 19]. On impact, greater mean peak loading rates have been documented at the front foot (298 $BW \cdot s^{-1}$) when compared to the back foot (79 $BW \cdot s^{-1}$) [15]. These forces coincide with lower trunk movements known to produce high contralateral facet joint contact forces, and have been posited as a major cause of lower back injury in fast bowlers [17-19]. Attenuated forces are transmitted to the lumbo-sacral junction via trunk hyperextension, and torsional forces by way of lateral flexion and twisting during the delivery stride are also endured [20]. Despite the considerable and differential musculoskeletal stresses encountered by fast bowlers, only limited studies have investigated the skeletal characteristics of this population, with much of the existing work focusing on the biomechanical factors underlying performance and the epidemiology of injury [16, 18, 19, 21].

To date, only two studies have investigated bone properties in elite fast bowlers using dual-energy X-ray absorptiometry (DXA), with both elite fast bowlers [7] and cricketers in general [14] possessing greater total-body bone mineral content (BMC) compared to controls. Adjusted for age and height, cricketers also demonstrate greater bone mineral density (BMD) for the total-body, proximal femur, femoral neck and lumbar spine, with no site-specific differences between playing positions [14]. More recently, we have observed greater unilateral differences in the arm BMC of fast bowlers compared to controls, alongside greater BMC of the bowling versus the non-bowling arm [7]. In addition to BMC and BMD, DXA images of the proximal femur can be utilised to obtain geometrical measures that are associated with bone strength. Hip structural assessment (HSA) provides quantification of bone geometry in the narrow regions parallel to thin cross-sectional slices of bone at specific locations throughout the proximal femur. This method compares favourably to volumetric qualitative computed tomography (QCT) [22] and enables DXA-derived data to be expressed in ways that are more mechanically interpretable, such that the geometric properties that underlie the prognostic value of BMD measurements can provide deeper insights into bone strength.

Given the unique loading environment associated with fast bowling [15, 16, 19], the characterisation of both total and unilateral femoral bone structure in bowlers would provide valuable insights with relation to hip structural characteristics and surrogate measures of bone strength. We therefore undertook the study presented here, with the specific objectives of: 1) characterising hip geometrical and structural qualities in fast bowlers and normally-active controls, and 2) in the fast bowlers, investigate potential asymmetry in bone strength between the front (leading in the delivery stride) and back (balancing in the delivery stride) leg proximal femur that might be reflective of the differential loading endured during the delivery phase.

Methods

Study design

The present study was carried out using a cross-sectional research design.

Participants

The participants were twenty-six (n = 26) elite male fast bowlers from a first-class county cricket club and twenty-six (n = 26) recreationally-active (< 3 sports-specific sessions per week) controls matched for age and ethnicity. The age range of both groups was 16 to 36 years. The descriptive characteristics for each group are presented in Table 1. Written informed consent was obtained prior to completing the study and all procedures were carried out in accordance with the Declaration of Helsinki, following approval by the University Faculty Research Ethics Committee.

Basic anthropometry and body composition

Stature was measured using a stadiometer (SECA Alpha, Birmingham, UK) and recorded to the nearest 0.1 cm. Body mass was measured using calibrated electronic scales (SECA Alpha 770, Birmingham, UK) and recorded to the nearest 0.1 kg. Body mass index (BMI) was calculated as mass/height^2. Shoes and jewellery were removed and lightweight clothing was worn for all physical measurements. Participants received one total-body and one total-hip DXA scan (GE Lunar iDXA, GE Healthcare, UK) during the cricket preseason (January) in a rested (refrained from intensive exercise in the preceding 12 hours), fasted and euhydrated state (urine osmolality <700 mOsmol·kg^{-1}) [23] in line with established recommendations [24]. For the total-body scan, participants were instructed to lie in a supine position on the scanning table, with arms to the side and ankles supported with the Lunar ankle strap (0.5 cm space between the ankles). Total-body fat mass, lean tissue mass (LTM), BMC and percentage tissue fat mass (%TFM) values were ascertained.

Bone mineral density measurements

Areal BMD was evaluated using DXA (Lunar iDXA, enCORE software, version 15.0, GE Healthcare, UK). Age and sex-specific United Kingdom reference data were used to calculate BMD Z-scores. Measurements were performed at the left and right proximal femur and the regions of interest were the femoral neck and trochanter.

Hip structural assessment

Structural geometry of the left and right proximal femur was determined from the acquired scans. These scans were analysed for bone structure and cross-sectional geometry by utilising the GE Lunar Advanced Hip Structural Analysis (HSA) programme. This was originally developed by Beck et al. [25] and based on the principles first described by Martin and Burr [26], which state that mass in a pixel value calibrated in g/cm^2 of hydroxyapatite can be converted to linear thickness in cm by dividing by the effective mineral density of fully mineralised adult bone. The enCORE HSA software (version 15.0) provides a line of pixels traversing the bone axis which gives a projection of the surface area of bone in the cross-section. We report the results from the narrow neck (NN) region, located across the femoral neck at its narrowest point. At this analysis region, several measurement outcomes were obtained.

Cross-sectional area (CSA in cm^2; exclusive of soft tissue spaces), cross-sectional moment of inertia (CSMI, in cm^4), section modulus (*Z*) and femoral strength index (FSI) values were assessed using HSA. CSA is an index of strength in pure compression along the bone axis. CSMI is a component of bending strength used in engineering calculations. It takes into account the strength improvement resulting from bone that is placed farther outward from the bone axis. Section modulus is an index of strength in pure bending and is derived from the CSMI and the maximum distance from the profile centre of mass to the medial or lateral cortical margin (y) neutral axis to the outer bone surface in the plane of bending (y). FSI is a rough two-dimensional engineering estimate of strength relative to a fall impacting on the greater trochanter. It incorporates some subject information (height and body mass) and some geometry computed by the HSA method (y, CSMI, CSA, neck-shaft angle, hip axis length etc.) and is based on the work of Yoshikawa et al. [27].

The observed *in-vitro* coefficient of variation was low at less than 0.5% for the regular quality control scans of the Lunar calibration phantom. The *in-vivo* precision value (coefficient of variation; %CV) for total hip BMD in our laboratory is 0.6% [28]. DXA precision error for *Z*, CSMI and CSA are 4.5%, 3.7% and 3.1% respectively [29]. Scan analysis was performed by the same trained operator using the Lunar enCORE software (version 15.0, GE Healthcare, UK).

Statistical analyses

Comparisons of descriptive results between groups were undertaken using two-tailed *t*-tests, as were comparisons of unilateral bone properties in fast bowlers, to investigate any differences between the front (leading) and back (trailing) hips in the delivery stride. Cohen's *d* effect sizes were calculated and classified using the following threshold values: 0.2 = small, 0.5 = moderate, 0.8 = large [30].

Linear multivariate analyses were conducted to compare unadjusted and adjusted (for height and lean mass) bone properties between groups. Significant main effects were explored using Bonferroni post-hoc tests. Effect size was quantified using partial eta squared (η_p^2) and classified using the following criteria: 0.01 = small, 0.06 =

moderate, 0.14 = large [30]. Pearson's correlation analyses were used to investigate relationships between anthropometric and descriptive characteristics and hip geometry variables. Covariates were selected based on theoretical and actual relationships to bone density and structural variables. These statistical procedures were carried out using the SPSS software package (version 22.0, IBM Corp., Armonk, NY).

To gain a deeper understanding of the unadjusted differences between groups, binomial logistic regression analysis was used to generate several models to distinguish between cricketers and non-cricketers. These models were refined using a backward stepwise approach, with variables having $p > 0.1$ excluded. Outputs from the logistic regression models were fed into a receiver operating characteristic (ROC) model so that respective sensitivity and specificity scores could be calculated. These procedures were completed using 'in-house' algorithms written in 'R' (open source statistical software) and Matlab (Mathworks, Natick, USA). The level of significance for all analyses was set at $p \leq 0.05$.

Results

Descriptive characteristics

Table 1 presents the descriptive comparisons between sample groups. Fast bowlers were significantly taller, heavier and possessed greater LTM and BMC than controls, demonstrating large effects. Although strictly non-significant, there was a statistical trend ($p = 0.056$) towards reduced %TFM in the fast bowlers, which was matched by a moderate effect size. There were no differences in age, fat mass or BMI between the two groups (i.e. only small to trivial effects). A logistic regression model constructed using only the anthropometric variables: body fat percentage (b = -181.9, $p = 0.003$);

total fat mass (b = 6.897, $p = 0.008$); total lean mass (b = -7.278, $p = 0.009$); and total BMC (b = 0.010, $p = 0.003$); distinguished the fast bowlers from the controls with a high degree of accuracy (sensitivity = 92.3%, specificity = 92.3%; $p < 0.001$), as depicted in Figure 1.

****insert Table 1 about here****

****insert Fig. 1 about here****

Relationships between covariates and bone variables

In the fast bowling group, height was significantly correlated with CSMI ($r = 0.68$, $p < 0.001$) and section modulus (*Z* values) ($r = 0.49$, $p = 0.011$). Body mass was correlated with CSMI ($r = 0.45$, $p = 0.022$), CSA ($r = 0.54$, $p = 0.005$), and *Z* values ($r = 0.43$, $p = 0.028$). BMI was correlated with BMD at the femoral neck ($r = 0.40$, $p = 0.042$) and the trochanter ($r = 0.48$, $p = 0.013$). %TFM was correlated with BMD at the femoral neck ($r = 0.42$, $p = 0.034$). Fat mass was correlated with femoral neck BMD and CSA (both $r = 0.41$, $p = 0.036$). Lean mass was associated with CSMI ($r = 0.46$, $p = 0.019$).

In controls, height was associated with FSI ($r = -0.39$, $p = 0.048$) and CSMI ($r = 0.49$, $p = 0.010$). Body mass was correlated with BMD at the femoral neck ($r = 0.42$, $p = 0.033$), CSMI ($r = 0.43$, $p = 0.029$) and *Z* values ($r = 0.41$, $p = 0.036$). BMC was associated with BMD at the femoral neck ($r = 0.40$, $p = 0.044$), CSA ($r = 0.61$, $p = 0.001$) and *Z* values ($r = 0.46$, $p = 0.017$). No other significant associations were observed in either group.

Bone density and geometrical properties

Unadjusted and height and lean mass-adjusted data are given in Table 2. With respect to the unadjusted data, the fast bowlers had greater BMD at the femoral neck and trochanter compared to controls. Resistance to axial loads, as indicated by CSA, was also greater in fast bowlers, as were derived *Z* values. Resistance to bending forces in the form of CSMI was greater in fast bowlers, in addition to FSI. Large effect sizes were noted for all unadjusted comparisons.

****insert Table 2 about here****

After adjusting for height and lean mass, significantly greater BMD remained at the femoral neck and trochanter in fast bowlers (Table 2). CSA and *Z* values were also greater in fast bowlers, with comparisons supported by large and moderate effect sizes, respectively. However, no significant difference was noted in CSMI, and this was corroborated by a small effect size.

A second logistic regression model was created using just the unadjusted hip geometry variable 'femoral neck BMD' (b = 8.479, $p < 0.001$) as a predictor. Whilst this model did not distinguish between the cricketers and non-cricketers as well as the model generated using the anthropometric characteristics, it was still able to differentiate between the two groups with a high degree of accuracy (sensitivity = 80.8%, specificity = 84.6%; $p < 0.001$) as illustrated in Figure 2.

****insert Fig. 2 about here****

Unilateral bone properties

When comparing the hip structural geometry of fast bowlers between the front (leading) and back (trailing) femur in the delivery stride, no significant differences were found

(Table 3). Greater FSI was observed at the back proximal femur, which despite not reaching statistical significance, yielded a small effect size. All other comparisons were non-significant and comprised trivial effects.

****insert Table 3 here****

Discussion

To our knowledge, this is the first study of proximal femur bone geometry in elite cricket fast bowlers and the first to explore surrogates of unilateral bone strength in relation to gravitational, axial and torsional loading. The key findings were that elite fast bowlers exhibited greater hip BMD and altered bone geometry compared with the controls, a finding that was consistent for all bone properties except CSMI following adjustment for height and lean mass. Indeed, such was the magnitude of this effect that we could distinguish with accuracy >80% between cricketers and non-cricketers, using unadjusted femoral neck BMD as the sole variable (Fig. 2). This indicates that the hip structural geometry of the fast bowlers observed in this study was profoundly different from the age-matched control group. Whilst the controls were representative of recreationally-active young adults, their hip bones would not have been exposed to the unique stresses and strains associated with first-class cricket, and fast bowling in particular. As such, our findings support those of previous research [14], and suggest that the observed differences in bone structure, density and geometry may be due to modelling brought about by the specific stresses associated with fast bowling.

Bone is reflective of its habitual loading environment, and exposure to forces of sufficient magnitude, frequency and duration will instigate an osteogenic response. Our findings are consistent with previous studies of athletes and controls exploring DXA-derived BMD and HSA parameters, both in our laboratory [31] and elsewhere [14]. In the present study the fast bowlers demonstrated greater resistance to axial loads (both adjusted and non-adjusted CSA) and bending forces in the form of *Z*. Cumulatively, the superior bone status of the fast bowlers would suggest that these athletes may be at a lower risk for osteoporosis in later life, through an optimisation of peak bone mass during young adulthood. FSI is an index which accounts for age, sex, body mass, height and BMD, and the lower FSI observed in controls would indicate that fast bowlers may be more resilient to hip fracture, provided that these benefits are maintained into later adulthood [31]. As such, our findings may be of relevance to the osteogenic potential of the unique loading conditions in fast bowling and to ongoing concerns regarding the aetiology of increased injury risk in these athletes.

An important finding was the absence of bilateral differences in proximal femur bone properties, despite the differential loading conditions between the front and back leg during the delivery stride, as evidenced by force platform data [15]. Substantial gravitational forces are generated to the front limb during the fast bowling action and there are also large forces associated with rapid deceleration, with anterior-posterior braking forces of around two times body mass [17]. Our findings may be indicative of equivalent osteogenic loading between the leading and trailing hips, and future research using biomechanical and three-dimensional geometry data would enable this to be explored further.

Considerable evidence is available to demonstrate the osteogenic effects of axial [32, 33] and gravitational loading [31]. Specific to fast bowling, peak vertical ground reaction forces have been reported as 6.7 times body mass [16]. To our knowledge, this study is the first to report elevated surrogate measures of hip bone strength in these athletes. Evidence of the effects of muscle torsional forces on bone has been documented using animal models [13] and in studies of the unilateral limbs in tennis and baseball players [12, 34]. The muscle torsional forces experienced during fast bowling occur in the lumbo-pelvic region, with significant flexion and rotation, as well as engagement of the hip extensor muscles to maximise ball release speed [35]. The finding that bone properties were similar between the leading and trailing hip would suggest that both types of loading conditions are likely to serve as bone anabolic stimuli, thus representing a practically useful avenue for the design of exercise interventions to promote bone strength [32, 33].

Conclusions

The findings of this study demonstrate profound differences in hip structure, density and geometry between fast bowlers and recreationally-active controls. Fast bowlers appear to have superior resistance to axial loads and bending forces at the proximal femur, allied to greater indices of bone strength (FSI). Importantly, no asymmetries in proximal femur bone properties were identified, suggesting that both gravitational and torsional loading provide similar and positive osteogenic potential. These findings may be transferrable to the design of exercise interventions with the aim of promoting bone health, in the form of weight-bearing exercises and those that develop muscle torsional strength.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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Table 1. Descriptive characteristics of elite male fast bowlers and controls.

Variable	Controls (*n* = 26)	Fast Bowlers (*n* = 26)	P value	Cohen's *d*
Age (years)	24.3 ± 4.2	22.4 ± 5.7	0.186	0.38
Height (cm)	178.3 ± 7.6	186.7 ± 5.0	<0.001	1.31
Body mass (kg)	77.2 ± 8.8	86.7 ± 5.9	<0.001	1.27
BMI (kg/m^2)	24.3 ± 2.4	25.1 ± 1.9	0.170	0.37
Fat mass (kg)	15.6 ± 5.5	15.3 ± 2.9	0.815	0.07
LTM (kg)	57.8 ± 5.9	67.6 ± 4.3	<0.001	1.75
%TFM	20.9 ± 6.0	18.4 ± 2.8	0.056	0.53
BMC (g)	3183 ± 356	3888 ± 338	<0.001	2.03

Data presented as mean ± SD

BMC bone mineral content; *BMI* body mass index; *LTM* lean tissue mass; *%TFM* percentage tissue fat mass

Table 2. Comparison of unadjusted and adjusted (for height and lean mass) mean areal bone mineral density and geometry measurements at the narrow neck of the proximal femur in elite male fast bowlers and controls.

Variable	Controls (*n* = 26)	Fast Bowlers (*n* = 26)	P value	η_p^2
Unadjusted				
Femoral neck (g/cm^2)	1.715 ± 0.232	2.138 ± 0.185	<0.001	0.51
Trochanter (g/cm^2)	1.469 ± 0.219	1.811 ± 0.161	<0.001	0.45
CSA (mm^2)	304.3 ± 46.2	387.9 ± 39.8	<0.001	0.50
CSMI (mm^4)	28495 ± 6844	37525 ± 8401	<0.001	0.27
Section Modulus (cm^3)	1513 ± 294	1944 ± 292	<0.001	0.36
FSI	2.56 ± 0.63	3.16 ± 0.79	0.004	0.16
Adjusted				
Femoral neck (g/cm^2)	1.750 ± 0.224	2.104 ± 0.187	<0.001	0.43
Trochanter (g/cm^2)	1.483 ± 0.219	1.798 ± 0.159	<0.001	0.41
CSA (mm^2)	321.9 ± 42.4	370.2 ± 36.5	<0.001	0.28
CSMI (mm^4)	32167 ± 6147	33853 ± 6645	0.339	0.02
Section Modulus (cm^3)	1633 ± 273	1824 ± 256	0.012	0.12

Data presented as mean ± SD

CSA cross-sectional area, *CSMI* cross-sectional moment of inertia, *FSI* femoral strength index

Table 3. Comparison of hip structural analysis variables between the front (leading) and back (trailing) proximal femur in elite fast bowlers (n = 26).

Variable	Front (Leading)	Back (Trailing)	P value	Cohen's *d*
Femoral neck (g/cm^2)	1.431 ± 0.133	1.414 ± 0.120	0.154	0.13
Trochanter (g/cm^2)	1.205 ± 0.099	1.209 ± 0.117	0.638	0.04
CSA (mm^2)	257.6 ± 26.3	259.8 ± 29.9	0.448	0.08
CSMI (mm^4)	24891 ± 5511	25236 ± 6021	0.382	0.06
Section Modulus (cm^3)	1287.2 ± 194.2	1309.5 ± 215.7	0.270	0.11
FSI	2.03 ± 0.63	2.25 ± 0.70	0.191	0.33

Data presented as mean ± SD

CSA cross-sectional area, *CSMI* cross-sectional moment of inertia, *FSI* femoral strength index

Figure Legend

Fig. 1 Plot of the logit and the probability of being a cricketer for the first logistic regression model, derived from the anthropometric variables only (age, height, weight, BMI, %TFM, total fat mass, LTM, and BMC).

Fig. 2 Plot of the logit and the probability of being a cricketer for the second logistic regression model, using femoral neck BMD as the sole predictor.