Bone cross sectional geometry and bone strength in male athletes exposed to differential loading modalities and non-athletic controls: an advanced hip structural analysis study

Running head: Femoral bone geometry in male athletes and controls

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Abstract

Loading of the skeleton can be achieved through weight-bearing exercise which is important for the development of a functionally and mechanically appropriate bone structure. Our objectives were to determine hip cross-sectional geometry in elite male athletes (n=54) subjected to different loading modalities (gymnastics, endurance running and swimming) and non-athletic, age-matched controls (n=20). Dual energy X-ray absorptiometry (iDXA, GE Healthcare, UK) measurements of the total body (for body composition) and the left proximal femur were obtained. The Advanced Hip Structural Analysis (AHA) programme was used to determine conventional areal bone mineral density (aBMD), hip axis length (HAL), cross-sectional area (CSA), and cross -sectional moment of inertia (CSMI). Bone strength indices were derived using the femoral strength index (FSI) (Yoshikawa et al, 1994). Gymnasts and runners had significantly greater age, height and weight adjusted aBMD than swimmers and controls ($p<0.05$). Gymnasts and runners had greater resistance to axial loads (CSA) and runners had increased resistance against bending forces (CSMI), compared to swimmers and controls ($p<0.01$). Hip axis length was greater in controls and this group also had lower indices of bone strength (FSI) compared to gymnasts and runners (1.4 *vs* 1.8 and 2.1 respectively, $p<0.005$). Lean body mass correlated significantly with aBMD, CSA and FSI ($r=0.365$-0.457, $p<0.01$) and correlations were stronger in controls ($r=0.657$-0.759, $p<0.005$). Our findings suggest the importance of regular physical loading and lean mass for promoting bone density and bone structural properties. Further research examining the contribution of different loading modalities to specific skeletal geometrical properties would be of value to inform strategies directed at maximising bone strength and thus fracture prevention, through sport and exercise.

Key words: Femoral neck, bone structure, exercise

Introduction

The architecture of the skeleton is unique and complex; functioning to provide support, protection and strength whilst also being light enough to enable the body to move. Equally as vital, bone tissue is also extremely dynamic, and continuously responds to diverse biochemical and physical stimuli. One such major stimulus is physical loading of the skeleton and this can be achieved through weight-bearing exercise of an appropriate magnitude, frequency and loading distribution.

During childhood and young adulthood, bone modelling and remodelling serves to optimise bone strength which can be enhanced through functional loading. (Seeman, 2008). Physical loading through weight-bearing exercise provides an oestrogenic stimulus to bone, which is essential for the development of a functionally and mechanically appropriate skeleton, thus the attainment of an optimal peak bone mass. This phenomenon is comprehensively described in the Mechanostat theory, which proposes that when all else is equal, individuals who are physically active should have stronger bones than their less active peers. More specifically, the Mechanostat theory indicates that in order for loading to generate sufficient strain, the loading should be a) of sufficient magnitude to elicit a response, b) distributed to the skeleton in abnormal directions; and c) exerted at a regular frequency (Schoenue, 2005). It is also known that the skeletal response to loading is site-specific (Sugiyami et al, 2010). The majority of conventional weight-bearing exercise generate loading to the lower limbs, and reflecting this, studies reporting positive effects, have done so for the regions of the hip as described in recent reviews of this literature (Hind and Burrows, 2007; Nikander et al, 2010). This is of particular importance because the hip, and in particular, the femoral neck; is the skeletal site at which osteoporotic fractures are most common and most devastating.

Fractures occur when loading exceeds the capacity of the bone to withstand them. Over the last 5 years, research has confirmed that this capacity is dependent on both the mineral density of the bone, and on the bone structural geometrical properties (Faulkner et al, 2006; Leslie et al, 2009; LaCroix et al, 2010). Dual energy X-ray absorptiometry (DXA) continues to be the preferred method for the assessment of bone mass and the diagnosis of osteoporosis because of low dose radiation, high accuracy and precision, and because it is quick to perform and non-invasive. However, the traditional DXA outcome, areal bone mineral density (aBMD), does not depict the geometrical properties of bone.

Recent models of DXA now include the measurement facility; hip structural analysis (HSA). This utilises properties of the DXA image to obtain geometrical measures that are associated with bone strength. HSA assesses bone geometry in the narrow regions parallel to thin cross sectional slices of bone at specific locations throughout the proximal femur. The method has been compared favourably to volumetric qualitative computed tomography (QCT) (Prevrhal et al, 2008) and enables DXA-derived data to be expressed in ways that are more mechanically interpretable so that the geometric properties that underlie the prognostic value of BMD measurements can provide critical insights into bone strength. The results from HSA have been used in studies as indices of bone strength to predict hip fracture (Faulkner et al, 2006; Leslie et al, 2009), to inform about sexual and ethnicity dimorphism in bone strength and fracture (Wang et al, 2005; Yates et al, 2007), evaluate associations with exercise during growth (Janz et al, 2007) and assess the effects of weight-bearing exercise interventions on bone (Petit et al, 2004).

Despite the increase in the availability and use of HSA, there have been no studies evaluating HSA parameters in male athletes from different sports. The characterisation of femoral bone structure in athletes may provide insights into how different activities may influence bone strength and would contribute to our understanding about the optimal exercises to promote bone strength. The objective of this current study therefore, was to determine whether the geometric expression of DXA-derived bone qualities differ between male athletes and non-athletic controls and between male athletes from different sports. We hypothesised that, corresponding to the loading produced by certain sports, geometric strength and aBMD would be greater in male gymnasts and runners compared to swimmers and non-athletic controls.

Materials and methods

Participants

Male endurance runners, gymnasts, swimmers and non-athletic controls were recruited to participate in the study. Participants had been recruited for 2 separate DXA-related studies within the Carnegie Research Institute, and results were collated for the current study. Endurance runners were recruited from athletics clubs and from an advertisement in a popular running magazine. Gymnasts were recruited from the Carnegie Regional Gymnastics Centre, and were members of the national squad, and swimmers were from a regional swimming club. Non athletic controls were recruited from the University. We administered a questionnaire to determine medical and injury history (including stress fractures) and exercise training. The age criteria for participation in the study were 18 to 35years. All runners were Caucasian and no participants had any medical condition or were using any medications or supplements that might interfere with bone metabolism. The male athletes were all competing at national or international standard and were involved in sport-specific training for at least 5 hours per week for the last 3 years. The Leeds NHS Research Ethics Committee and the University Research Ethics Committee reviewed and approved the study and informed consent was obtained from all participants.

Anthropometry

Participants wore light-weight clothing and removed shoes and jewellery for all physical measurements. Standing height was measured using a stadiometer (SECA, Birmingham, UK) and recorded to the nearest millimetre. Body mass was measured with calibrated electronic scales (SECA, Birmingham, UK) and recorded in kilograms (kg) to the nearest 0.1 kg. Body mass index (BMI) was calculated by using the formula, of [body mass (in kg)/ height (in metres) ^{2} (kg/m^{2})].

Body composition

Body composition was also measured in all participants using dual energy X-ray absorptiometry (Lunar iDXA™ fan beam densitometer with enCORE software, GE Medical Systems, UK) of the total body, and variables included fat percentage and lean mass.

Bone mineral density measurements

Areal BMD was evaluated using DXA (Lunar iDXA, enCORE software 12.45, GE Healthcare, UK). Age and sex-specific UK reference data was used to calculate BMD Z-scores. Measurements were performed at the left total proximal femur. Short term in-vivo precision for DXA measurements in our DXA Unit, of the total proximal femur in adults is 0.6% (Hind et al, 2010). 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.

Hip structural analysis

Structural geometry of the left proximal femur was determined from the scans acquired and described above. These scans were analysed for bone structure and cross sectional geometry by utilising the advanced Hip Structural Analysis (AHA) programme. This was originally developed by Beck et al (1990) and based on the principles first described by Martin and Burr (1984) which states 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 AHA software version 12.45 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 region (NN) across the femoral neck at its narrowest point. At this analysis region, several measurement outcomes were obtained.

Hip axis length (HAL), cross sectional area (CSA in cm^2; exclusive of soft tissue spaces), cross-sectional moment of inertia (CSMI, in cm^4) and femoral strength index (FSI) were obtained using HSA. HAL is a measurement of the length of the femoral neck and head, and this has been proven to be an independent predictor of fracture risk. CSA is an indicator of axial strength and is taken following the *y* axis along the NN (*y* is the distance from the centre of mass to the superior neck margin). CSMI is a measurement of density and the distribution of the density around the femoral neck. It reflects periosteal apposition that brings the bone mineral further away from the central axis, thus increasing bone strength. FSI is an advanced feature which has been added to more recent versions of enCORE and can be used for investigative purposes to indicate the risk of fracture for forces generated during a fall on the greater trochanter. It combines BMD, femur geometry, age, height and body mass, and is calculated as strength/stress, where stress is moment * *y* /CSMI + force /CSA, and is based on work by Yoshikawa et al (1994).

Statistical analyses

Statistical tests were performed using SPSS version 17.0 (LEAD Technologies Inc©). Descriptive statistics (means and standard deviations) were used to characterise the sample and the comparative groups. Comparisons of descriptive results between groups were made using one-way analysis of variance (ANOVA), followed by the Bonferroni post-hoc test. Linear multivariate analyses were conducted to calculate marginal means for bone variables after correction for age, height and weight, and Bonferroni pairwise comparisons were computed between groups. Pearson's correlation analyses were used to evaluate relationships between the anthropometric and body composition variables and bone structural measures in participants. Covariates were selected based on theoretical and actual relationships to bone density and structural variables. The level of significance was set at $p<0.05$.

Results

Descriptive statistics

Participant descriptive are summarised in Table 1. Runners were older than gymnasts ($p=0.034$) and gymnasts were shorter in height than runners ($p=0.002$), swimmers ($p=0.016$) and controls ($p=0.002$). Runners weighed less than than swimmers ($p=0.004$) and controls ($p=0.001$), and controls had higher body fat percentage than runners ($p=0.006$) and gymnasts (p=0.001). Differences in lean mass between groups did not reach statistical significance (p>0.05).

Table 1 Anthropometric measures and demographic characteristics of male athletes and non athletic controls

Bone density and geometric results

Bone density and geometrical results for each group before correction for age, height and weight, are provided in Table 2. Gymnasts had significantly greater areal BMD of the proximal femur compared to runners (p=0.016) and controls (p=0.005). After adjustment for age, height and weight, gymnasts and runners had greater areal BMD than controls (p=0.04; p=0.045).

HAL was shorter in swimmers compared to runners (p=0.03) and controls (p=0.03). Gymnasts had a larger CSA of the NN than swimmers (p=0.012) and controls (p=0.004), and runners had a larger CSA than controls (p=0.018). These differences continued after correction for age, height and weight (p<0.05). CSMI was greater in runners than gymnasts and controls (p<0.04) and after correction for age, height and weight, in runners than in swimmers (p=0.02) and controls (p=0.01).

FSI was greater in runners compared to swimmers (p=0.001) and controls (p=0.001), and in gymnasts compared to controls (p=0.015). After adjustment for age, height and weight, these differences remained (p<0.05).

Table 2 Comparison of areal bone mineral density (aBMD) and bone geometry measurements in the narrow neck region of the proximal femur between male athletes and non-athletic controls. *HAL* hip axis length; *CSA* cross sectional area; *CSMI* cross sectional moment of inertia; *FSI* femoral strength index

Relationships between covariates and bone variables

In all participants age, height and weight were correlated with bone area of the femoral neck (r=0.516, r=0.516, and r=0.238 respectively; p<0.05). Age, weight and lean mass were correlated with femoral neck areal BMD (r=-0.347, r=0.262, and r=0.468 respectively; p<0.05). Although there were no differences between groups in lean mass, there was a significant association between lean body mass and the hip structural variables of both CSA (r=0.444, p<0.001; Fig. 1) and CSMI (r=0.260, p<0.05). Height and weight were also associated with CSA (R=0.413, R=0.366; p<0.01) and CSMI (r=0.538, r=0.365; p<0.001). Following adjustment for age, height and weight, lean mass was positively correlated with BMD (r=0.395, p=0.003), CSA (r=0.457, p=0.002) and FSI (r=0.365, p=0.039). There were no associations with percentage body fat.

Fig. 1: Correlation between lean body mass and cross sectional area of the femoral narrow neck

There were no correlations between age and bone variables when groups were analysed separately. Correlations between anthropometry and lean mass with bone variables were higher in the controls, particularly for the associations of lean mass with BMD (r=0.759, p<0.001), CSA (r=0.752, p<0.001) and FSI (r=0.657, p<0.001). In runners and gymnasts, lean mass only correlated with CSMI (r=0.509 p=0.02, and r=0.671 p=0.012 respectively). In gymnasts, height was also a significant predictor of CSMI (r=0.554, p=0.01).

Discussion

This is the first study to investigate DXA advanced hip structural analysis--derived geometrical properties of the femoral neck in elite male athletes exposed to different loading modalities through sport. In support of our hypothesis, we found that male gymnasts and runners had greater resistance to axial loads (CSA) and that runners had increased periosteal apposition (which augments bone strength through greater resistance against bending forces) (CSMI), compared to elite swimmers and non-athletic, age-matched controls. Hip axis length, which is an independent risk factor for hip fracture in adult populations, was increased in the non-athletic control group and this group also had lower indices of bone strength (FSI) compared to gymnasts and runners. The differences in strength properties remained significant after adjusting for differences in age, body size (height) and weight, which in accordance with the literature demonstrating associations between HSA measures and fracture (Faulkner et al, 2006; Leslie et al, 2009), suggests that gymnasts and runners may have a degree of protection against hip fracture.

Periosteal apposition reduces bone fragility by adding more bone mass to the skeleton and increases stiffness and strength by adding bone further away from the central axis (Turner, 2003). Importantly, we observed indications of greater periosteal apposition in runners compared to swimmers and non-athletic controls. This supports the number of animal studies that have demonstrated periosteal expansion with increased mechanical loading (Pederson et al, 1999; LaMothe et al, 2005). Interestingly, we also found lower CSMI in gymnasts, potentially reflective of the lower age of the gymnasts, through the knowledge that bone width through periosteal apposition also increases during young adulthood (Riggs et al, 2004).

Hip structural variables and bone density were strongly related with anthropometric measurements (body size and body weight) and total lean body mass. It is known that individuals of short stature will have lower areal BMD measurements than their taller counterparts. However, although being of smaller stature, gymnasts had greater BMD than all groups, which suggests superiority in bone mineral and strength. Importantly, and in agreement with several previous studies (DiVasta et al, 2007; Travison et al, 2008), total lean body mass was found to be a significant predictor in measures of BMD, CSA, CSMI, and FSI, whereas total body fat percentage was not. Lean body mass is recognised as a surrogate for the muscle loading forces that direct bone adaptation. Furthermore, previous research has demonstrated that dynamic forces rather than static forces provide the greatest osteogenic stimulus (Lanyon and Rubin, 1984; Forwood and Turner, 1995). Our results are supportive of this in that greater total lean mass was associated with greater bone strength measurements. Our sample comprised of athletic groups and a non-athletic control group, and of relevance, the association between lean mass and hip structural properties were strongest for the control group. This is suggestive of the functional muscle-bone unit (Schoenue, 2005) and further highlights the importance of lean body mass for bone strength. It is likely that the forces provided through physical loading such as gymnastics, which provides high magnitude loading in abnormal directions; exerts an additional, advantageous influence on bone strength.

Some potential limitations should be considered when interpreting the results of this study, in terms of the population and analyses. The participant groups were not equal, with only 9 participants in the group of swimmers, and small numbers could limit the generalisability of our findings. Additionally participants were male, and therefore our findings are not applicable to females, who differ in terms of bone development and peak bone mass accrual. BMD, assessed by 2D image technique such a DXA, is an estimate of the average amount of mineral per unit area in a section of bone facing the detector. Since the hip strength indices assessed by AHA are estimated by use of the same mass distribution curve as BMD measurement, both CSA and CSMI depend on the amount of mineral present in the femoral neck, and consequently are not totally independent of BMD.

In summary, gymnasts and runners had superior resistance to axial loads at the hip compared to swimmers and age-matched, non-athletic controls. This may offer a lower risk against fracture, particularly through the greater observed FSI outcomes. Runners also had greater resistance to bending loads through higher CSMI. Lean body mass was predictive of hip structural properties in all participants, and in particular, in non-athletic controls, which suggests a beneficial action of lean mass even in the absence of regular mechanical loading through sport, and supports previous research emphasising the importance of the muscle-bone unit. In conclusion, the hip structural analysis programme is useful for acquiring insights into bone strength beyond conventional BMD. We highlight the value of regular physical loading and lean mass for promoting bone density and bone structural properties. Further research examining the contribution of different loading modalities to specific skeletal geometrical properties would be of value to inform strategies directed at maximising bone strength and thus fracture prevention, through sport and exercise.

References

DiVasta AD, Beck TJ, Petit M, et al. Bone cross sectional geometry in adolescent girls and young women with anorexia-nervosa: a hip structural analysis study. Osteoporos Int. 2007;18:797-804

Faulkner KG, Wacker WK, Barden HS, et al. Femur strength index predicted hip fractures independent of bone density and hip axis length. Osteoporos Int 2006;17:4:593-599

Forwood MR, Turner CH. Skeletal adaptations to mechanical usage: results from tibial loading studies in rats. Bone. 1995;17:4:S197-S205

Hind K and Burrows M. Weight-bearing exercise and bone mineral accrual in children and adolescents: a systematic review of controlled trials. Bone 2007; 40:14-27

Janz KF, Gilmore JM, Levy SM, et al. Physical activity and femoral neck bone strength during childhood: the Iowa bone development study. Bone 2007;41:2:216-222

Lanyon LE, Rubin CT. Static vs dynamic loads as an influence on bone remodelling. J Biomech. 1984;17:897-905

LaCroix AZ, Beck TJ, Cauley JA et al. Hip structural geometry and incidence of hip fracture in postmenopausal women: what does it add to conventional bone mineral density? Osteoporos Int 2010;21:6:919-929

LaMothe JM, Hamilton NH, Zerricke RF, et al. Strain rate influences periosteal adaptation in mature bone. Med Eng Phys. 2003;27:4:277-284

Leslie WD, Pahlavan PS, Tsang JF, et al. Prediction of hip and other osteoporotic fractures from hip geometry in a large clinical cohort. Osteoporos Int. 2009;20:10:1767-1774

Nikander R, Sievanen H, Heinonen A, et al. Targeted exercise against osteoporosis: a systematic review and meta-analysis for optimising bone strength throughout life. BMC Medicine. 2010;8:47:1-16

Pederson EA, Akhler MP, Cullen DM, et al. Bone response to in vivo mechanical loading in C3H/HeJ mice. Calcif Tiss Int. 1999;65:1:41-46

Petit M, Beck TJ, Lin HM, et al. Femoral bone structural geometry adapts to mechanical loading and is influenced by sex steroids: the Penn State Young Women's Health Study. Bone 2004;35:750-759

Prevrhel S, Shepherd JA, Faulkner KG et al. Comparison of DXA hip structural analysis with volumetric QCT. J Clin Densitom 2008;11:2:232-236

Riggs BL, Melton 3rd, Robb RA, et al. Population study of age and sex differences in bone volumetric density, size, geometry and structure at different skeletal sites. J Bone Miner Res. 2004;19:2:1945-1954

Schoenue E. From the mechanostat theory to the development of the 'functional muscle-bone unit'. J Musculoskel Neuronal Interact. 2005; 5:2:232-238

Seeman E. Structural basis of growth related gain and age-related loss of bone strength. Rheumatol 2008;47:4:2-8

Sugiyami T, Price JS, Lanyon LE. Functional adaptation to mechanical loading in both cortical and cancellous bone is controlled locally and confined to the loaded bones. Bone. 2010;46:2:314-321

Travison TG, Araujo AB, Esche GR, et al. Lean mass and not fat mass is associated with male proximal femur strength. J Bone Min Res. 2008;23:2:189-198

Turner CH. Periosteal apposition and fracture risk. J Musculokel Neuron Interact. 2003; 3:4:410

Wang XF, Duan Y, Beck TJ, et al. Varying contributions of growth and ageing to racial and sex differences in femoral neck structure and strength in old age. Bone 2005;36:978-986

Yates LB, Karasik D, Beck TJ, et al. Hip structural geometry in old and old-old age: similarities and differences between men and women. Bone 2007; 41:4:722-732

Yoshikawa T, Turner CH, Peacock M, et al. Geometric structure of the femoral neck measured using dual X-ray absorptiometry. J Bone Miner Res 1994;9:1053-1064

Table 1 Anthropometric measures and demographic characteristics of male athletes and non athletic controls

Characteristics	Runners	Gymnasts	Swimmers	Controls
Age (years)	27.2 ±4.4*	22.0 ±2.0	23.2 ±4.3	26.4±5.4
Height (cm)	178.9±7.2	170.9±7.5*	179.8±4.1	178.7±5.5
Weight (kg)	68.4±7.0	69.8±8.2	78.7±7.2*	76.8±7.9*
Lean mass (kg)	54.0±5.5	57.8±5.0	61.3±5.4	56.8±6.0
Percentage body fat	16.3±4.4	13.2±3.7	15.6±3.5	22.8±5.4*

*Significantly different p<0.05

Table 2 Comparison of areal bone mineral density (aBMD) and bone geometry measurements in the narrow neck region of the proximal femur between male athletes and non-athletic controls. *HAL* hip axis length; *CSA* cross sectional area; *CSMI* cross sectional moment of inertia; *FSI* femoral strength index

Variable	Runners	Gymnasts	Swimmers	Controls
aBMD (g/cm^2)	1.089±0.11	1.217±0.14*	1.140±0.07	1.063±0.01
HAL	121.7±6.6	111.7±5.0*	113.8±6.7*	123.4±7.3
CSA (mm^2)	202.5±24.8*	202.2±23.5*	197.8±23.5	187.1±25.3
CSMI (mm^4)	194.9±41.5*	164.2±38.9	173.1±39.8	180.0±37.1
FSI	2.06±0.3*	1.8±0.1*	1.5±0.3	1.4±0.3

Fig. 1: Correlation between lean body mass and cross sectional area of the femoral narrow neck