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Pelvis width associated with bone mass distribution at the proximal femur in children 10–11 years old

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Abstract

Differences in skeletal geometry may generate different patterns of mechanical loading to bone. Impact and muscle loading during physical activity have been shown to influence skeletal geometry. The purpose of this study was to compare geometric measures of the pelvis and proximal femur (PF) of young children and to analyze the contribution and potential interaction of these geometric measures with physical activity on PF bone mass distribution. Participants were 149 girls and 145 boys, aged 10–11 years. Total body and left hip DXA scans were used to derive pelvic and PF geometric measures and PF bone mineral density (BMD) at the femoral neck (FN), trochanter (TR), and intertrochanter (IT). These subregions were used to represent bone mass distribution via three BMD ratios: FN:PF, TR:PF, and IT:PF. Physical activity was objectively measured using accelerometry, and maturity was estimated as the years of distance from peak height velocity. When compared to boys, girls had a wider pelvic diameter and greater interacetabular distances ($p < 0.001$), lower BMD at FN, TR, and IT ($p < 0.05$), and higher TR:PF ($p < 0.001$). After controlling for maturity, body height, and lean body mass, the interacetabular

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distance in girls explained 21.1 % ($\beta = 0.713$, $p < 0.001$) in TR:PF and 2.9 % ($\beta = -0.179$, $p = 0.031$) in the IT:PF. Neck–shaft angle explained 5.6 % ($\beta = -0.265$, $p = 0.001$) of the IT:PF and 3.1 % ($\beta = 0.194$, $p = 0.018$) of the FN:PF. In boys, FN axis length explained 2.9 % ($\beta = 0.195$, $p = 0.040$) of TR:PF. There was no main effect of physical activity or interaction effect with pelvic geometry in explaining BMD differences among the subregions of the PF. Even before sexual dimorphism, girls have a wider pelvis than boys, which accounted for proportionally greater BMD of the TR than other subregions of the PF.

Keywords

Bone; Children; Pelvis; Physical activity; Proximal femur

Introduction

Intervention programs to maximize bone mineral accrual during late childhood and early adolescence are a promising approach to offset age-related bone loss and the risk of fracture in later life [1, 2]. Peripubertal growth is a critical period for skeletal mineralization [3, 4], and better adaptive bone responses are expected during this time with adequate mechanical loading via physical activity [5–7]. The hypothesis of a sex-specific bone response to physical activity has been raised, suggesting that the skeleton is less sensitive to mechanical loading in girls than in boys [8–10]. Recently, a study with 325 boys and girls aged 9–10 years showed heterogeneous response to vigorous physical activity in the three subregions of the proximal femur in girls but homogeneous response in boys [11]. This hypothesis of different skeletal sensitivity to site-specific mechanical loading during late childhood and early adolescence may partly explain why women face a greater risk of fragility fractures in old age [12–16] and stress fractures in early adulthood [17, 18].

In addition, there is a known association between bone geometry of the pelvis and the proximal femur with bone fracture risk [19–21]. Larger neck–shaft angles (NSA) and longer hip axis lengths or femoral neck axis lengths (FNAL) have a greater association with cervical fractures than trochanteric fractures [19]. These associations could result from (only) the effect of bone geometry on bone strength or alternatively might be influenced by the interaction between bone geometry and mechanical loading on bone mineralization and ultimately strength.

Because of the biomechanics of the hip, it is plausible that the geometry of the pelvis–proximal femur structure might moderate mechanical forces exerted on the proximal femur and, therefore, result in different degrees of mineralization among proximal femur subregions. Accordingly, the objectives of this study were (1) to compare geometric measures of the pelvis and proximal femur—the interacetabular distance (IAD), FNAL, and NSA, among others—between girls and boys aged 10–11 years and (2) to analyze the contribution of these geometric measures to the variance of bone mass distribution at the proximal femur. For this purpose, bone mineral density (BMD) ratios between each proximal femur subregion (femoral neck, trochanter, and intertrochanter) and the integral proximal femur were used as surrogates of proximal femur bone mass distribution. As a

third aim, we investigated interactions between these geometric measures and objectively measured habitual physical activity on proximal femur bone mass distribution. The latter aim is important because physical activity is one of the few known modifiable factors to reduce fracture risk.

Materials and methods

Sample

Study participants were drawn from Oeiras schools (fifth grade). The total sample was composed of 294 children (139 boys and 146 girls), after excluding 22 who were more than 11 years old. All participants were healthy Caucasian students not taking any medication known to influence bone metabolism. The Ethics Committee of the Faculty of Human Movement, Technical University of Lisbon approved the study, and parents or legal guardians of each child provided written informed consent.

Proximal femur bone mass distribution

Integral BMD of the left proximal femur and BMD of each proximal femur subregion were evaluated using dual X-ray absorptiometry (DXA) (QDR Explorer; Hologic, Waltham, MA, USA) and standard measurement routines. Three BMD ratios were calculated as indicators of BMD homogeneity of the proximal femur:

$$\begin{aligned} FN : PF &= \frac{\text{Neck BMD}}{\text{Proximal femur BMD}} \\ TR : PF &= \frac{\text{Trochanter BMD}}{\text{Proximal femur BMD}} \\ IT : PF &= \frac{\text{Intertrochanter BMD}}{\text{Proximal femur BMD}} \end{aligned}$$

where FN:PF is the femoral neck to proximal femur BMD ratio, TR:PF is the trochanter to proximal femur BMD ratio, and IT:PF is the intertrochanter to proximal femur BMD ratio.

All measurements were made by the same technician, and a spine phantom was scanned daily to maintain quality assurance. The coefficients of variation of the femoral neck, the trochanter, and the intertrochanter BMD, estimated from two measurements by repositioning and scanning 28 subjects were 1.6 %, 1.7 %, and 1.3 %, respectively.

Pelvis and femur geometric measures

Linear geometric measures of pelvis and proximal femur were determined by DXA for each subject from images of whole body and left hip scans, respectively. All images were saved and appropriately transformed in grayscale (using Adobe Photoshop Elements) to be used as an input for the geometric morphometric software, the Thin-Plate Spline Digitize (tpsDigQ1) software Version 2.10 [22]. This program and its procedures are described in detail elsewhere [22]. With tpsDigQ1, several two-dimensional (2D) landmarks (x, y coordinates) were digitized in every single image, namely, eight 2D landmarks in the pelvis image (Fig. 1) and twenty 2D landmarks in the proximal femur image (Fig. 2), with each point referring always to the same shape feature. To comply with tpsDigQ1 requirements, the scale of the scanned images was done at the femur using the Ward's area, as in previous report [23]. At the pelvis, a metal object (4.4 cm × 9.5.6 cm) was scanned and merged with

the pelvis images (Fig. 1). Estimation of linear geometric measures in the pelvis included the largest inner diameter of the pelvic bone (LIDP); the lower interacetabular distance (LIAD), defined as the distance between the left and the right lower points of the acetabular opening ($\overline{AA'}$ in Fig. 1); the upper interacetabular distance (UIAD), defined as the distance between the left and the right upper points of the acetabular opening ($\overline{BB'}$ in Fig. 1); and the IAD, calculated as the distance between left and right middle points of the previous references ($\overline{CC'}$ in Fig. 1).

Estimation of geometric measures in proximal femur included the FNAL, defined as the linear distance measured from the base of the greater trochanter to the apex of the femoral head [24] ($\overline{AB}$ in Fig. 2), the NSA, defined as the angle between the femoral neck axis ($\overline{AB}$ in Fig. 2), and the femoral shaft axis ($\overline{CD}$ in Fig. 2). The femoral neck width (FNW), defined as the distance across the femoral neck, often constrained to being perpendicular to the neck axis ($\overline{EF}$ in Fig. 2), was also measured.

Because the accuracy of DXA scans in measuring bone geometry is quite sensitive to the patient's position during imaging, strictly standard protocols for positioning and analysis of DXA scans were followed. The reproducibility of the measurements was calculated by three blind repeated measurements of the geometric measures from DXA images. The root mean square of coefficient of variations was between 0.4 % and 0.5 % for LIAD, IAD, UIAD, and NSA, 0.8 % for LIDP, 2.8 % for FNW, and 2.2 % for FNAL.

Physical activity

Habitual (nontargeted) physical activity was assessed using the GT1M accelerometer (Actigraph, Fort Walton Beach, FL, USA) with 15-s epochs. Participants wore the monitor for 4 days (two weekdays and two weekend days), providing at least 600 min per day of accelerometer data. Those not complying with these requirements were excluded from the sample. The accelerometer was secured on the right hip, and the children were asked to wear the accelerometer all day, except during water activities and sleeping. Activity data were analyzed and processed using the MAHUFFe analysis program (<http://www.mrc-epid.cam.ac.uk>). The output from the program included accumulated time spent at sedentary-, light-, moderate-, and vigorous-intensity physical activity in minutes per day. The intensity of physical activity was defined according to the counts per minute (cpm) as follows: sedentary activity, up to 100 cpm; light intensity (LPA), from 101 to 2,295 cpm; moderate intensity (MPA), from 2,296 to 4,011 cpm; and vigorous intensity (VPA), more than 4,012 cpm [25].

Historical sport activity participation relevant to the musculoskeletal system was assessed with the bone-specific physical activity questionnaire (BPAQ), a validated tool that accounts for bone-relevant loading [26] and records current and historical activity. Under the supervision of a researcher, participants were asked to record all regular sport activities practice, including approximate duration, throughout their lives (historical activity) as well as during the previous 12 months, including frequency of participation (current activity). Using the evidence-based osteogenic index described by Turner and Robling [27], an

algorithm was applied to convert the raw BPAQ data into an individual score that reflects total bone-relevant sports activity history.

Body size and body composition

Standing and sitting height were measured to the nearest 0.1 cm using a stadiometer (Secca 770, Hamburg, Germany) with children in underwear and barefoot. Body mass (kg), total fat (kg), and total lean mass without bone (kg) were determined from a total-body scan using DXA (QDR Explorer; Hologic, Waltham, MA, USA) with children in a fasting state. Body mass index (BMI) was calculated as body mass in kilograms divided by height (in meters) squared.

Maturity and calcium intake

Maturity ($\pm$ years) was estimated as the years of distance positive or negative from the age of peak height velocity using sex-specific prediction equations that include age, body height, and sitting height [28]. The calcium intake (mg) was calculated from a semiquantitative Food Frequency Questionnaire, assessing regular intake of a wide set of typical Portuguese foods.

Statistical analysis

Data were analyzed using the SPSS statistical software package (version 18.0 for Windows; SPSS, Chicago, IL, USA). Distribution properties of all variables were examined, and appropriate measures of central tendency and variability were selected. Differences between groups (girls and boys) were analyzed by independent samples *t* tests in case of normality and Mann–Whitney nonparametric tests otherwise. Stepwise linear regressions models were used to analyze the associations between geometric-related variables of the pelvis and proximal femur (as independent variables), first with each of the subregional BMDs and then with the three BMD ratios (as dependent variables). All regression models were controlled for maturity, body height, and body lean mass. Initial models pooled boys and girls to test the significance of sex as a predictor variable and then separately. In every case, the assumptions for the linear regression analysis were verified (normality and linearity of the residuals, multicollinearity, and homoscedasticity).

Sex-specific multivariate analysis of covariance (MANCOVA) was used to analyze main and interaction effects of moderate- and vigorous-intensity physical activity and geometric measures on the three BMD ratios of the proximal femur. The physical activity and geometric variables were set as fixed factors and grouped as below (group 1) or above (group 2) the mean (when variable distribution was normal) or below and above the median (in case of no normality). Maturity, body height, and body lean mass were covariates. Normality of distribution and homogeneity of variance assumptions required to conduct MANCOVA were verified using the Kolmogorov–Smirnov test and the Levene's test, respectively. Statistical significance was set at $p < 0.05$.

Results

Sample characteristics including body composition and physical activity are presented in Table 1. Compared to boys, girls were more mature, taller, and had greater fat mass. Weight, lean body mass, and light-intensity physical activity were similar between boys and girls. Boys had less sedentary time and greater levels of moderate- and vigorous-intensity physical activity, as assessed by accelerometry, when compared to girls. However, there were no statistically significant differences between sexes concerning BPAQ variables.

Bone variables are presented in Table 2. BMD was greater in boys at the integral proximal femur as well as at all three subregions. There were no differences between boys and girls for bone mass distribution (as defined using ratios) at the femoral neck and intertrochanter. However, TR:PF was greater for girls ($p < 0.001$) than for boys. All measured geometric variables of the pelvis were wider in girls when compared with boys. The FNW was wider in boys than in girls ($p < 0.001$). The proximal femur NSA and the FNAL means did not differ between girls and boys ($p > 0.05$).

Positive associations of both body lean, mass and physical activity with BMD at all proximal femur subregions were observed in linear regression analyses (Table 3).

However, the physical activity variable that entered each model (with the best explanatory contribution) was not always the same: moderate- and vigorous-intensity physical activity entered in all the three boys' models whereas in girls, moderate- and vigorous-intensity physical activity entered in the femoral neck BMD model, vigorous-intensity physical activity entered in the trochanter BMD model, and moderate-intensity physical activity in the intertrochanter BMD model.

The results of linear regression models for the three BMD ratios—FN:PF, TR:PF, and IT:PF—are presented in Table 4. In girls, the NSA was positively associated with the FN:PF ($\beta = 0.194$, $p = 0.018$). The NSA explained 3.1 % of FN:PF, suggesting that a larger NSA contributes to a greater relative mineralization of the femoral neck region. IAD was positively associated with TR:PF ($\beta = 0.713$, $p < 0.001$), explaining 21.1 % of the variance. The NSA ($\beta = -0.265$, $p = 0.001$) and the IAD ($\beta = -0.173$, $p = 0.031$) were inversely associated with the IT:PF. In boys, the FNAL was positively associated with the TR:PF ($\beta = 0.195$, $p = 0.040$), explaining 2.9 % of the variance. With the exception of the IT:PF model in girls, no physical activity variable was associated to the relative mineralization of the subregions of the proximal femur.

As a follow-up, MANCOVA analysis of BMD ratios was conducted for girls (Table 5). In these models, the IAD and moderate- and vigorous-intensity physical activity were set as fixed factors and body height, maturity, and body lean mass used as covariates. Moderate- and vigorous-intensity physical activity was not a main effect, nor did it interact with IAD for any BMD ratios. The lack of main effect and lack of interaction was true for all other physical activity intensities substituted in these models: data not shown. Consistently with the regression analysis results, a wider pelvis in girls was associated with a higher mean TR:PF (0.826 vs. 0.791, $p = 0.01$) and lower mean IT:PF (1.104 vs. 1.117, $p = 0.039$).

The analysis conducted for boys was similar, but IAD was replaced by the FNAL as fixed factor, given that the IAD did not turn out to be significant in any of the previous boys' regressions (Table 6).

None of the fixed factors—the geometry-related variable, here the FNAL, or moderate- and vigorous-intensity physical activity—was a main effect, nor did they interact with each other, for any BMD ratios.

Discussion

Available data have shown that women and men tend toward differing pelvic types [29–33] and that sex-related differences are evident early in life even during the gestation period [34, 35]. However, there is a lack of research addressing geometric differences of the pelvis in children. The objectives of this research were (1) to compare linear geometric measures of the pelvis and proximal femur between girls and boys aged 10–11 years, (2) to analyze the contribution of these geometric measures to the variance of the bone mass distribution at the proximal femur, and (3) to investigate interaction effects between geometric measures and physical activity on bone mass distribution at the proximal femur. Three BMD ratios—FN:PF, IT:PF, and TR:PF—were used as surrogates of the bone mass distribution at the proximal femur. This is a novel approach that controlled for intersubject variability in timing and tempo of mineralization by creating measures of intraindividual relative difference of mineralization at the proximal femur. The main findings indicated that girls have a wider pelvis than boys, which helps to explain their proportionally greater trochanter BMD when compared to other subregions of the proximal femur. Our findings also indicated that distinctive features of the pelvis are associated with proximal femur bone mass distribution.

In the present study, a wider pelvis in girls was associated with proportionally greater BMD in the trochanter (compared with neck and intertrochanter subregions) and lower BMD in the intertrochanter (compared with the neck and trochanter proximal femur subregions). However, this latter contribution was small ($R^2 = 3.1\%$) compared to the contribution of a wide pelvis in explaining the variance of the TR:PF ($R^2 = 21.1\%$). Similar relationships were not found in boys, perhaps as consequence of a much lower interacetabular distance variation coefficient (0.056) in boys when compared to girls (0.074). When boys and girls were analyzed together (data not shown), the relationship between interacetabular distance and the TR:PF was also significant ($\beta = 0.494$, $R^2 = 8.8\%$, $p < 0.001$).

The importance of the width of pelvis in girls for a proportionally greater BMD of the trochanter compared to other subregions of the proximal femur might be explained by the biomechanics of the hip [36, 37]. Mechanical loads exerted on the proximal femur are a consequence of a complex system of vector forces, axis, and levers that depend on the geometry of both the pelvis and the proximal femur [38]. A wider pelvis increases the torque exerted by the body mass on the pelvis–proximal femur joint and, so long as it promotes a valgus thigh type of posture, requires a stronger action of the abduction muscles on the proximal femur to counterbalance the body mass forces [36, 37]. As the attachment of these muscles into the proximal femur is done at the great trochanter, the corresponding modeling effects would be observable at this region [39, 40]. During childhood, the largest

physiological bone loads are from muscle forces and not from gravity forces because of the disadvantageous positioning of muscle insertions on the bony lever [41]. Therefore, our result associating a wider pelvis (expressed by interacetabular distances) to a relatively more mineralized trochanter is consistent with running and jumping intervention studies that report the greatest intervention effect on the trochanter [42, 43]. Of key importance is the fact that a wider pelvis and running/jumping interventions engage the same muscles [44]. The biomechanics of the hip should apply to both girls and boys. However, we did not see this effect in our sample of boys. Schwarzkopf et al. [45], nevertheless, observed that the wideness of the pelvis was an important factor in determining how forces are exerted on the different regions of the proximal femur. Their work simulated forces and stresses transmitted through the proximal femur via a finite element analysis model developed from the basic model of the pelvis–hip biomechanics: $a \times B \times a = ALA \times A$, where a is the proportion of the body weight (B) supported by the standing leg while the opposite leg swings during single leg stance, a is the body weight lever arm, ALA is the abductor lever arm, and A is the abductor force needed to balance the pelvis. They simulated the stresses for a wide and a narrow pelvis, concluding that the maximum principal stress on the femoral neck is 1.7 times lower in the narrower pelvis model.

In our study, the NSA in girls and the FNAL in boys were explanatory variables for the bone mass distribution of the proximal femur and, so far as these variables integrate the geometric characteristics of the proximal femur, corroborate the hypothesis that the geometry of the proximal femur may influence the relative mineralization of the three subregions of the proximal femur. However, in contrast to the interacetabular distance, these two variables were not geometric features that differed between boys and girls, and thus could not justify a possible sex-specific response to physical activity. We are aware that the pelvis–hip biomechanics suggest other more (theoretically) relevant geometric measures of the proximal femur, such as the abductor lever arm, but these data were not available for the present study.

We expected a main effect and perhaps an interaction effect between pelvis geometry and physical activity in the BMD of a specific bone region, particularly in the region of maximum stress [45]. This effect was not observed, suggesting that physical activity has equivalent effects on the three subregions in boys and girls.

The use of DXA in our study provided low exposure to radiation and a clinically relevant site (proximal femur). However, DXA use brought a set of well-known limitations not only associated to its 2D nature but also our quantitative measurement technique. An image technique such as plain radiography would have provided greater resolution and improved the location of landmarks. In addition, we used the whole-body scan images for the pelvis, making this task even more challenging. To overcome these limitations, Photoshop options to enhance image contrast and quality were essential. The young age of our participants was another limitation because until the end of puberty there are only small sex differences in body shape and composition. Finally, cross-sectional studies are vulnerable to confounding by unrecognized determinants and cohort effects are also present. A longitudinal study including additional biomechanical-related variables would mitigate some of these drawbacks.

In conclusion, children aged 10–11 years have sex-specific pelvic geometry differences, with girls having a wider pelvis than boys. In girls, this geometric aspect accounted for a proportionally greater BMD of the trochanter than the other subregions of the proximal femur. Physical activity showed a positive association with the absolute BMD of the three regions of the proximal femur in both sexes, but did not have any effect nor did it interact with pelvic geometry to explain relative BMD of a particular subregion of the proximal femur. The findings support the hypothesis that differences between boys and girls in bone mass distribution among neck, trochanter, and intertrochanter proximal femur subregions may be better explained by pelvis width than by differences in gender-specific physical activity responsiveness.

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Fig. 1.

Geometric measures of the pelvic bone. **I** Diagram illustrating the pelvic measures: $A \leftrightarrow A'$, lower interacetabular distance (LIAD); $B \leftrightarrow B'$, upper interacetabular distance (UIAD); $C \leftrightarrow C'$, interacetabular distance (IAD); $D \leftrightarrow D'$, largest inner diameter of the pelvic bone (LIDP).

II Dual-energy X-ray absorptiometry (DXA) image of one of our subjects with metal object (E) inserted to show the scale of scanned images

Fig. 2. Geometric measures of the proximal femur: $A \leftrightarrow B$, femoral neck axis length (FNAL); $C \leftrightarrow D$, femoral shaft axis; $E \leftrightarrow F$, femoral neck width (FNW); NSA, neck-shaft angle; 1–3, landmarks representing middle distance of neck width; 4–6, landmarks representing middle distance of shaft width

Table 1

Participants characteristics: age, maturity, body composition, and physical activity as mean $\pm$ standard deviation

	Girls (<i>n</i> = 146)	Boys (<i>n</i> = 139)	<i>p</i> *
Age, years	10.3 $\pm$ 0.5	10.3 $\pm$ 0.5	0.315 ^a
Maturity offset, years	-1.19 $\pm$ 0.6	-2.87 $\pm$ 0.5	<0.001
Peak high velocity, years	11.5 $\pm$ 0.5	13.2 $\pm$ 0.6	<0.001
Body height, cm	145.8 $\pm$ 7.1	143.5 $\pm$ 6.6	0.005
Weight, kg	40.6 $\pm$ 9.2	38.4 $\pm$ 9.1	0.008 ^a
Body mass index, kg/m ²	19.0 $\pm$ 3.5	18.6 $\pm$ 3.6	0.186 ^a
Body fat, kg	12.3 $\pm$ 5.5	10.3 $\pm$ 5.7	<0.001 ^a
Body lean mass, kg	28.3 $\pm$ 4.7	28.1 $\pm$ 4.2	0.808
Body fat, %	29.3 $\pm$ 7.1	25.4 $\pm$ 7.7	<0.001 ^a
Calcium intake, mg/day	1,062 $\pm$ 58	1,277 $\pm$ 92	0.105 ^a
Sedentary, min/day	1,076 $\pm$ 70	1,056 $\pm$ 70	0.020 ^a
Light PA, min/day	245 $\pm$ 38	243 $\pm$ 39	0.587
Moderate PA, min/day	27.9 $\pm$ 9.6	34.9 $\pm$ 13	<0.001
Vigorous PA, min/day	11.2 $\pm$ 7.0	15.5 $\pm$ 9	<0.001 ^a
Moderate and vigorous PA, min/day	39.1 $\pm$ 14	50.3 $\pm$ 21	<0.001 ^a
PA average intensity, count/min/day	400 $\pm$ 108	452 $\pm$ 132	0.001 ^a
Past BPAQ, score	9.86 $\pm$ 16.42	8.15 $\pm$ 12.87	0.121
Current BPAQ, score	13.58 $\pm$ 26.59	10.74 $\pm$ 15.02	0.183
Total BPAQ, score	23.45 $\pm$ 36.16	18.88 $\pm$ 20.94	0.096

PA physical activity, BPAQ bone-specific physical activity questionnaire

* Student's *t* test comparing boys to girls

^a In cases of no normality, Mann–Whitney nonparametric tests were used

Table 2Participants characteristics: BMD and bone geometric measures as mean $\pm$ standard deviation

	Girls (<i>n</i> = 146)	Boys (<i>n</i> = 139)	<i>p</i> *
Proximal femur BMD, g/cm ²	0.731 $\pm$ 0.08	0.773 $\pm$ 0.08	<0.001
Neck BMD, g/cm ²	0.694 $\pm$ 0.08	0.740 $\pm$ 0.08	<0.001
Trochanter BMD, g/cm ²	0.592 $\pm$ 0.08	0.611 $\pm$ 0.07	0.028
Intertrochanter BMD, g/cm ²	0.812 $\pm$ 0.09	0.856 $\pm$ 0.10	<0.001
Neck/proximal femur BMD	0.950 $\pm$ 0.05	0.957 $\pm$ 0.05	0.198
Trochanter/proximal femur BMD	0.809 $\pm$ 0.05	0.790 $\pm$ 0.04	<0.001
Intertrochanter/proximal femur BMD	1.110 $\pm$ 0.03	1.107 $\pm$ 0.03	0.532
Neck–shaft angle, (°)	134.9 $\pm$ 5.2	134.7 $\pm$ 5.7	0.642
Femoral neck axis length, cm	7.18 $\pm$ 0.54	7.22 $\pm$ 0.50	0.591
Femoral neck width, cm	2.56 $\pm$ 0.20	2.62 $\pm$ 0.20	0.005
Interacetabulum distance, cm	12.7 $\pm$ 0.9	12.3 $\pm$ 0.7	<0.001
Upper interacetabulum distance, cm	13.9 $\pm$ 1.0	13.6 $\pm$ 0.8	0.007
Lower interacetabulum distance, cm	11.5 $\pm$ 0.9	11.0 $\pm$ 0.7	<0.001
Largest inner distance of pelvic bone, cm	8.4 $\pm$ 0.9	8.0 $\pm$ 0.6	<0.001

BMD bone mineral density* Student's *t* test comparing boys to girls^a In cases of no normality, Mann–Whitney nonparametric tests were used

Table 3

Regression coefficients (β), level of significance (p), and coefficient of determination (R^2) of the associations between physical activity, geometric measures of pelvis, and proximal femur BMD, adjusted for maturity, body height, and lean body mass

	Predictor variable	Girls			Predictor Variable	Boys		
		β	p	R^2		β	p	R^2
Neck BMD	LBM	0.657	<0.001	0.467	LBM	0.405	<0.001	0.173
	ModVig PA	0.211	0.001	0.044	ModVig PA	0.393	<0.001	0.155
	FNAL	-0.118	0.104	<i>a</i>	FNAL	-0.069	0.404	<i>a</i>
	FNW	-0.136	0.056	<i>a</i>	FNW	-0.004	0.962	<i>a</i>
	IAD	-0.128	0.200	<i>a</i>	IAD	-0.071	0.511	<i>a</i>
	Moderate PA	0.050	0.753	<i>a</i>	Moderate PA	-0.116	0.668	<i>a</i>
	Vigorous PA	-0.037	0.753	<i>a</i>	Vigorous PA	0.085	0.430	<i>a</i>
	Total PA	-0.045	0.752	<i>a</i>	Total PA	0.175	0.483	<i>a</i>
	Past BPAQ	0.040	0.505	<i>a</i>	Past BPAQ	0.038	0.615	<i>a</i>
	Current BPAQ	0.003	0.959	<i>a</i>	Current BPAQ	0.041	0.578	<i>a</i>
	Total BPAQ	0.021	0.730	<i>a</i>	Total BPAQ	0.054	0.473	<i>a</i>
	Body height	-0.133	0.160	<i>a</i>	Body height	-0.166	0.181	<i>a</i>
	Maturity offset	0.029	0.801	<i>a</i>	Maturity offset	-0.180	0.213	<i>a</i>
Trochanter BMD	LBM	0.434	<0.001	0.427	LBM	0.552	<0.001	0.156
	Vigorous PA	0.161	0.011	0.021	ModVig PA	0.387	<0.001	0.087
	IAD	0.250	0.018	0.022	Body height	-0.316	0.016	0.033
	FNAL	-0.011	0.890	<i>a</i>	FNAL	0.003	0.972	<i>a</i>
	FNW	-0.018	0.813	<i>a</i>	FNW	-0.047	0.605	<i>a</i>
	Moderate PA	0.056	0.479	<i>a</i>	IAD	0.006	0.962	<i>a</i>
	ModVig PA	0.088	0.479	<i>a</i>	Moderate PA	-0.257	0.369	<i>a</i>
	Total PA	0.085	0.460	<i>a</i>	Vigorous PA	0.187	0.369	<i>a</i>
	Past BPAQ	0.026	0.682	<i>a</i>	Total PA	0.135	0.604	<i>a</i>
	Current BPAQ	-0.001	0.982	<i>a</i>	Past BPAQ	0.086	0.269	<i>a</i>
	Total BPAQ	0.011	0.863	<i>a</i>	Current BPAQ	0.096	0.210	<i>a</i>
	Body height	-0.003	0.974	<i>a</i>	Total BPAQ	0.128	0.106	<i>a</i>
	Maturity offset	0.087	0.474	<i>a</i>	Maturity offset	-0.316	0.724	<i>a</i>
Intertrochanter BMD	LBM	0.591	<0.001	0.372	LBM	0.569	<0.001	0.227
	Moderate PA	0.142	0.035	0.020	ModVig PA	0.374	<0.001	0.136
	FNAL	-0.045	0.584	<i>a</i>	FNW	-0.202	0.012	0.030
	FNW	-0.095	0.232	<i>a</i>	FNAL	0.015	0.865	<i>a</i>
	IAD	-0.143	0.199	<i>a</i>	IAD	-0.160	0.123	<i>a</i>
	Vigorous PA	0.010	0.909	<i>a</i>	Moderate PA	-0.129	0.616	<i>a</i>
	ModVig PA	0.020	0.909	<i>a</i>	Vigorous PA	0.094	0.616	<i>a</i>
	Total PA	-0.060	0.585	<i>a</i>	Total PA	-0.003	0.989	<i>a</i>
	Past BPAQ	-0.047	0.481	<i>a</i>	Past BPAQ	0.117	0.109	<i>a</i>
	Current BPAQ	-0.031	0.645	<i>a</i>	Current BPAQ	0.036	0.603	<i>a</i>

Predictor variable	Girls			Predictor Variable	Boys		
	β	p	R^2		β	p	R^2
Total BPAQ	-0.045	0.508	<i>a</i>	Total BPAQ	0.097	0.176	<i>a</i>
Body height	-0.071	0.509	<i>a</i>	Body height	-0.214	0.079	<i>a</i>
Maturity offset	0.081	0.529	<i>a</i>	Maturity offset	-0.099	0.471	<i>a</i>

BMD bone mineral density, *LBM* lean body mass, *FNAL* femoral neck axis length, *FNW* femoral neck width, *IAD* interacetabular distance, *PA* physical activity, *ModVig PA* moderate and vigorous physical activity, *BPAQ* bone-specific physical activity questionnaire

^aVariable with nonsignificant coefficient, not entered into the model

Table 4

Regression coefficients (β), level of significance (p), and coefficient of determination (R^2) of the associations between physical activity, geometric measures of pelvis, and proximal femur BMD ratios, adjusted for maturity, body height, and body lean mass

	Predictor variable	Girls			Predictor variable	Boys		
		β	p	R^2		β	p	R^2
Neck/proximal femur BMD	NSA	0.194	0.018	0.031	FNW	0.391	<0.001	0.084
	LBM	0.190	0.021	0.036	LBM	-0.199	0.035	0.029
	FNAL	-0.056	0.583	<i>a</i>	NSA	0.074	0.362	<i>a</i>
	FNW	-0.129	0.183	<i>a</i>	FNAL	-0.062	0.562	<i>a</i>
	IAD	-0.115	0.396	<i>a</i>	IAD	0.154	0.207	<i>a</i>
	LPID	-0.188	0.061	<i>a</i>	LPID	0.172	0.077	<i>a</i>
	Body height	-0.091	0.484	<i>a</i>	Body height	0.156	0.262	<i>a</i>
	Maturity offset	-0.006	0.971	<i>a</i>	Maturity offset	-0.059	0.703	<i>a</i>
	Moderate PA	0.113	0.168	<i>a</i>	Moderate PA	0.017	0.833	<i>a</i>
	Vigorous PA	0.108	0.186	<i>a</i>	Vigorous PA	0.006	0.938	<i>a</i>
	ModVig PA	0.124	0.132	<i>a</i>	ModVig PA	0.013	0.871	<i>a</i>
Trochanter/proximal femur BMD	IAD	0.713	<0.001	0.211	Body height	-0.328	0.001	0.055
	LBM	-0.318	0.009	0.037	FNAL	0.195	0.040	0.029
	NSA	-0.041	0.573	<i>a</i>	NSA	-0.010	0.903	<i>a</i>
	FNAL	0.147	0.111	<i>a</i>	FNW	0.107	0.335	<i>a</i>
	FNW	0.111	0.220	<i>a</i>	IAD	0.168	0.156	<i>a</i>
	LPID	0.023	0.869	<i>a</i>	LPID	0.032	0.766	<i>a</i>
	Body height	0.143	0.234	<i>a</i>	Maturity offset	-0.137	0.306	<i>a</i>
	Maturity offset	-0.004	0.976	<i>a</i>	LBM	-0.081	0.563	<i>a</i>
	Moderate PA	0.006	0.935	<i>a</i>	Moderate PA	0.032	0.700	<i>a</i>
	Vigorous PA	0.118	0.109	<i>a</i>	Vigorous PA	0.050	0.542	<i>a</i>
	ModVig PA	0.060	0.419	<i>a</i>	ModVig PA	0.042	0.612	<i>a</i>
Intertrochanter/proximal femur BMD	NSA	-0.265	0.001	0.056	Maturity offset	0.327	0.001	0.051
	Vigorous PA	-0.183	0.022	0.035	FNW	-0.193	0.038	0.074
	IAD	-0.173	0.031	0.029	NSA	-0.143	0.081	<i>a</i>
	FNAL	0.097	0.325	<i>a</i>	FNAL	0.178	0.095	<i>a</i>
	FNW	-0.000	0.999	<i>a</i>	IAD	-0.076	0.506	<i>a</i>
	LPID	0.103	0.485	<i>a</i>	LPID	-0.108	0.286	<i>a</i>
	Body height	-0.027	0.813	<i>a</i>	Body height	0.047	0.739	<i>a</i>
	Maturity offset	0.109	0.344	<i>a</i>	LBM	0.200	0.218	<i>a</i>
	LBM	0.136	0.306	<i>a</i>	Moderate PA	-0.051	0.536	<i>a</i>
	Moderate PA	0.055	0.584	<i>a</i>	Vigorous PA	-0.065	0.426	<i>a</i>
	ModVig PA	0.086	0.584	<i>a</i>	ModVig PA	0.060	0.464	<i>a</i>

BMD bone mineral density, PA physical activity, ModVig PA moderate and vigorous physical activity, NSA neck–shaft angle, LBM lean body mass, FNAL femoral neck axis length, FNW femoral neck width, IAD interacetabular distance, LPID largest inner pelvic diameter

^aVariable with nonsignificant coefficient, not entered into the model

Table 5

Main and interaction effects of interacetabular distance and physical activity on proximal femur BMD ratios in girls, adjusted for maturity, body height, and body lean mass

	Girls (n = 149)						
	Interacetabular distance			Physical activity (moderate + vigorous)			Interaction^a
	<IAD^b	>IAD^b	p	<ModVig PA^b	>ModVig PA^b	p	p
Neck/proximal femur BMD	0.952 ± 0.007	0.948 ± 0.007	0.726	0.946 ± 0.005	0.954 ± 0.006	0.281	0.292
Trochanter/proximal femur BMD	0.791 ± 0.006	0.826 ± 0.006	0.001	0.806 ± 0.005	0.811 ± 0.005	0.470	0.829
Intertrochanter/proximal femur BMD	1.117 ± 0.004	1.104 ± 0.004	0.039	1.114 ± 0.003	1.107 ± 0.003	0.162	0.466

Cutoff values: 12.70 cm for IAD; 37.28 min/day for physical activity of moderate or higher intensity

BMD bone mineral density, IAD interacetabular distance, PA physical activity, ModVig PA moderate and vigorous physical activity

^a IAD × ModVig PA

^b Values are expressed as mean ± standard error

Table 6

Main and interaction effects of femoral neck axis length and physical activity on proximal femur BMD ratios in boys, adjusted for maturity, body height, and body lean mass

	Boys (<i>n</i> = 142)						
	Femoral neck axis length			Physical activity (moderate + vigorous)			Interaction^a
	<FNAL^b	>FNAL^b	<i>p</i>	<ModVig PA^b	>ModVig PA^b	<i>p</i>	<i>p</i>
Neck/proximal femur BMD	0.960 ± 0.006	0.954 ± 0.006	0.474	0.960 ± 0.006	0.962 ± 0.006	0.238	0.415
Trochanter/proximal femur BMD	0.786 ± 0.005	0.793 ± 0.005	0.357	0.789 ± 0.005	0.790 ± 0.005	0.874	0.568
Intertrochanter/proximal femur BMD	1.106 ± 0.003	1.108 ± 0.003	0.620	1.109 ± 0.003	1.105 ± 0.003	0.367	0.522

Cutoff values: 7.22 cm for FNAL; 47.54 min/day for physical activity of moderate or higher intensity

BMD bone mineral density, FNAL femoral neck axis length, PA physical activity, ModVig PA moderate and vigorous physical activity

^a FNAL × ModVig PA

^b Values are expressed as mean ± standard error