Adolescent Physical Activity and Bone Strength at the Proximal Femurin Adulthood

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ABSTRACT

JACKOWSKI, S. A., S. A KONTULAINEN, D. M. COOPER, J. L. LANOVAZ, T. J. BECK, and A. D. BAXTER-JONES. Adolescent Physical Activity and Bone Strength at the Proximal Femurin Adulthood. *Med. Sci. Sports Exerc.*, Vol. 46, No. 4, pp. 736–744, 2014. **Introduction**: Physical activity (PA) enhances bone structural strength at the proximal femur in adolescence, but whether these benefits are maintained into early adulthood remains unknown. The purpose of this study was to investigate whether males and females, described as active, average, and inactive during adolescence, display differences in structural strength at the proximal femur in early adulthood (20–30 yr). **Methods**: One hundred four participants (55 males and 49 females) from the Pediatric Bone Mineral Accrual Study (PBMAS) were categorized into adolescent PA groupings (inactive, average, and active) using the Physical Activity Questionnaire for Adolescents. Cross-sectional area and section modulus (*Z*) at the narrow neck, intertrochanter, and femoral shaft (S) sites of the proximal femur were assessed using hip structural analysis in young adulthood from femoral neck dual-energy x-ray absorptiometry scans. Group differences were assessed using ANCOVA, controlling for adult height (Ht), adult weight (Wt), adolescent bone geometry, sex, percentage adult total body lean tissue (LTM%), and adult PA levels. **Results**: Active adolescents had significantly greater adjusted bone geometric measures at all sites than their inactive classified peers during adolescence ($P < 0.05$). In adulthood, when adjusted for Ht, Wt, adolescent bone geometry, sex, LTM%, and adult PA levels, adolescent participants categorized as active had significantly greater adjusted adult bone geometric measures at the proximal femur than adult participants who were classified as inactive during adolescence ($P < 0.05$). **Conclusions**: Skeletal advantages associated with adolescence activity appear to confer greater geometric bone structural strength at the proximal femur in young adulthood. **Key Words:** HIP STRUCTURAL ANALYSIS, PHYSICAL ACTIVITY QUESTIONNAIRE, LEAN TISSUE MASS, BONE GEOMETRY, LONGITUDINAL

EPIDEMIOLOGY

Osteoporosis is a disease characterized by deterioration of the bone structure, leading to subsequent bone fragility (32). Hip fractures are arguably the most costly consequence of osteoporosis, resulting in increased mortality, compromised functional capacity, and an amplified economic burden on the public health care systems (32). Although the early determinants of osteoporosis and fracture risk are still poorly understood, it has been proposed that optimizing and maintaining bone structural strength, particularly during adolescence, can potentially reduce the risk of osteoporosis later in life (25).

According to the mechanostat theory, dynamic loads are essential to elicit bone adaptation (21). Physical activity (PA) via muscular actions places such loads on the skeleton and is documented to provide osteogenic benefits to bone structural strength during childhood, adolescence, and adulthood (2,14,28,42). Engaging in PA during childhood and adolescence is highlighted as a unique opportunity where the benefits of mechanical loading on bone structural strength can be maximized (1,4,20). In addition, the mechanostat theory suggests that the removal of these dynamic loads, or a reduction in PA, would result in negative bone adaptation with declines observed in both bone mass and bone structural strength (21). Supporting this supposition, immobilization studies have documented rapid declines in bone mass and structural parameters with the removal of dynamic loads (11,12,40). This would imply that to maintain any benefits to structural strength attained during childhood and adolescence, into young adulthood, PA levels should be maintained.

Although the Saskatchewan Pediatric Bone Mineral Accrual Study (PBMAS) provided evidence to support the supposition that skeletal benefits resulting from early life habitual PA persist into young adulthood (4), these results focused primarily on bone mineral content (BMC) accrual and areal bone mineral density (aBMD) development. Although bone strength generally trends in the same direction as aBMD and BMC, this is not always the case. In addition, these parameters

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are not themselves properties that govern strength. Bone strength is determined by structural dimensions (e.g., bone size and geometry) and material strength (9). It has been acknowledged that geometric measures may improve fracture prediction beyond that provided by aBMD alone, because cross-sectional area (CSA) and section modulus (*Z*) measures are better able to differentiate between osteoporotic and nonosteoporotic individuals (26,30,34). Retired athlete models have been commonly used to investigate the association between early life PA levels and adult geometric bone strength. Retired athletes have been reported to have significantly greater total bone area, CSA, and bending strength at cross-sections of the radius and humerus (16,19,28). These data suggest that childhood and adolescent PA is associated with not only improved bone mass but also improved bone geometric properties; however, such conclusions derived from retired athletes are confounded by the possibility of genetic predispositions. Muscle strength is a strong predictor of bone structural strength (15,22,35,36). PA and lean tissue mass development (3), a surrogate of muscle strength, are also strongly linked. Given these relationships, the independent role of PA on bone structural strength development may be confounded or masked by the effects of PA on lean tissue mass development. It is therefore suggested that investigations in healthy nonathletic populations that consider the confounding effects of lean tissue mass development would be more applicable to the general public and provide further evidence to support the investment of PA in childhood and adolescence (33).

Previously, in this cohort of healthy children participating in the PBMAS, it has been shown that higher levels of habitual PA are positively associated with the development of improved geometric bone measures at the hip during adolescence (20). Furthermore, geometric bone measures appear to peak and/or plateau between the second and third decade of life (23). What remains unknown is (i) whether the benefits of PA, observed during adolescence, are maintained into young adulthood and (ii) whether current adult PA influences maintenance of the bone benefits observed in adolescence. The longitudinal nature of the PBMAS provides a unique data set to address these questions. Therefore, the purpose of this present study is to investigate whether adolescent PA is related to geometric bone strength estimated at the proximal femur in young adulthood. It is hypothesized that once the confounders of height, weight, lean tissue mass, and adult PA levels are accounted, adults identified as active in adolescence will have greater CSA and *Z* at the proximal femur than adults classified as average and/or inactive in adolescence.

METHODS

Participants. Participants were drawn from the University of Saskatchewan's PBMAS. Details of the PBMAS participants and the recruitment process have been described previously (1,6). In brief, in 1991, 375 eligible students, age 8–15 yr, were recruited from two elementary schools in the city of Saskatoon, of which the parents of 228 students (113 boys and 115 girls) provided written consent for their children to be involved in the study. Two hundred twenty of these individuals underwent dual-energy x-ray absorptiometry (DXA) scans. From 1992 to 1993, an additional 31 participants were recruited and scanned. After 7 yr of annual data collection, 230 participants (109 males and 121 females) had been measured on two or more occasions (median, six occasions) and comprised the adolescent longitudinal data set. Between 2002 and 2007, 169 participants returned and were measured on at least one occasion (ages range, 17 to 30 yr). To be included in the present study, participants had to have: 1) a valid assessment of peak height velocity (PHV); 2) an assessment of peak geometric bone measures in adulthood (23); 3) PA scores at PHV and in adulthood; and 4) no diseases known to affect growth or bone development. This resulted in the inclusion of 104 participants (55 males and 49 females). Ninety-eight percent of the participants were Caucasian. Written informed consent (parental consent for minors) was obtained from all participants. All procedures were approved by the University of Saskatchewan's biomedical ethics review committee.

Anthropometry. Height and weight were assessed annually after the anthropometric standards outlined by Ross and Marfell-Jones (37). Height (Ht) was recorded without shoes to the nearest 0.1 cm using a wall-mounted stadiometer (Holtain Limited, Crymych, UK). Weight (Wt) was measured without shoes on a calibrated scale to the nearest 0.1 kg (Toledo, Columbus, OH).

PHV. The attainment of PHV, a measure of maximum linear growth during adolescence, is a commonly used maturational landmark in longitudinal studies (7). Given that maturity influences adolescent PA levels in both sexes in a contemporaneous manner (7,39), it is imperative that when assessing PA during adolescence, individuals be aligned at a comparable maturity milestone (7). To determine the age at PHV, whole year height velocities were calculated for each participant from serial measures of stature. A cubic spline fitting procedure was applied to each individual's whole year velocity values, and the age at the highest point was estimated (GraphPad Prism 5; GraphPad Software, San Diego, CA). The cubic spline curve fitting procedure provides a smooth velocity curved based on polynomial algorithms that maintain the original integrity of each individual's data. From these curves, an estimation of attainment of peak statural growth are identified.

PA and PA groupings. PA was serially assessed using self-report questionnaires. Details of the PA questionnaires used have been reported elsewhere (3). In brief, during childhood and adolescence, PA was assessed using the Physical Activity Questionnaire for Children (PAQ-C) and the Physical Activity Questionnaire for Adolescence (PAQ-A). The PAQ-C/A were designed to assess general PA levels over the previous 7 d, scoring nine items on a five-point Likert-type scale. Final PA scores range from one to five, with higher scores indicating higher levels of PA. In adulthood, the Physical Activity Questionnaire for Adults (PAQ-AD), a seven-item version of the PAQ-C/A, was used; again, individual PA was

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scored on a five-point scale. The PAQ-C/A/AD have been previously reported to be a valid and reliable measure of PA levels in children, adolescents, and adults (13,24,29).

Adolescent activity groups were formed on the basis of the PAQ-C/A scores using procedures described in detail elsewhere (5,17). Briefly, for each individual, an age- and sex-specific *Z* score was determined for each test administration. These *Z* scores were based on the mean and SD for the entire sample at the same chronological age. All childhood and adolescent *Z* scores, from each measurement occasion, were then summed and averaged, the median number of annual visits being 6 (minimum, 3; maximum, 7). Individuals were then ranked into quartiles according to their average adolescent activity *Z* score. Those whose *Z* score fell in the highest quartile were classified as active, those in the middle two quartiles were classified as average active, and those whose score was in the lowest quartile were classified as inactive.

To control for current adult PA, a PA score occurring when peak geometric bone measure were reached was ascertained using a linear interpolation routine (MatLab 2006b; Mathworks, Natick, MA) for each participant. This value (1 low to 5 high) was then used as the adult PA score specific to the geometric bone outcome measure (e.g., CSA or *Z*).

Total body lean tissue mass. Total body lean tissue mass (LTM) was assessed annually by DXA (Hologic QDR-2000, array mode; Hologic, Bedford, MA) by a trained technician following the procedures outlined in the operators manual and user guide. Adult LTM was determined as the adult values at the age at which the peak in geometric bone measures occurred for each individual. Total body lean tissue mass (LTM) was analyzed using software version 5.67A. The interassay precision (CV%) *in vivo* in our laboratory have been previously reported as 0.5% for LTM (3). LTM percentage (LTM%) was determined as the ratio of LTM (kg) to total body Wt (kg).

Bone measures. At each measurement occasion, participants underwent a DXA scan of the total body, lumbar spine, and proximal femur following the procedures outlined in Hologic operator's manual. For the current study, only proximal femur DXA scans were used, and all bone measures were derived using the hip structural analysis (HSA) program. The HSA program has been previously reported elsewhere in greater detail (10). In brief, the HSA program uses the two dimensional bone mass profiles derived from DXA to estimate the geometric properties of bone on the basis of the principles described by Martin and Burr (31). Martin and Burr (31) indicated that a line of pixels across a bone axis is equivalent to a cut plane traversing the bone at that location. According to this principle, the pixel mass profile can provide information on bone thickness, which in turn can be used to estimate geometric properties. Using the pixel mass profile, the HSA technique produces three 5-mm-thick cross-sectional regions for analysis, namely, 1) the narrow neck (NN)—the narrowest diameter of the femoral neck; 2) the intertrochanter (IT) site—along the bisector of the neck and shaft angle; and 3) the shaft (S)—a distance of 1.5 times the minimum neck width to the intersection of the neck and shaft axes. The HSA program locates these regions on the DXA bone mineral image and then derives the estimates of structural geometry. From each region, the HSA program produces 10 output variables, of which two were assessed for this study: cross-sectional area (CSA)—the estimated amount of bone surface area in the cross-section after excluding all the trabecular and soft tissue space; and section modulus (*Z*)—an indicator of bending strength calculated as the cross-sectional moment of inertia divided by the maximum distance from the center of mass to outer cortex (9,10). The short-term precision for CSA and *Z* derived using a Hologic QDR 2000 hip scan ranges from 2.3% to 2.8% and 2.8% to 3.4%, respectively (27). All HSA analyses were completed by a single technician (S. A. Jackowski) and derived from proximal femur scans using a Hologic QDR-2000.

Bone measures were identified at PHV and in young adulthood. In young adulthood, following the procedures previously outlined by Jackowski et al. (23), the ages and absolute values for maximal proximal femur CSA and *Z* were determined for each participant. The maximal values were determined as the maximal absolute value for each bone measure at each site, resulting in maximum values for CSA and *Z* at each site (e.g., NN, IT, and S). The ages at maximum were used to determine the time point for selecting adult covariates (e.g., Ht, Wt, LTM%, and PA scores).

Statistical analysis. Differences in adolescent CSA and *Z*, between adolescent PA groups, were first assessed using an ANOVA. This was performed to confirm previous observations in this population (5,20) that differences in geometric bone properties existed during adolescence between adolescent PA groups. To test for potential differences in adult peak bone geometric measures between adolescence PA groups, three progressive ANCOVA were performed. Males and females were pooled for these analyses because of the small sample sizes observed when sexes were separated. Power calculations determined that a sample size of 105 participants was sufficient to achieve 80% power (G-power 3.1.6). Instead, sex was included into all models as a covariate to determine potential sex differences. The first ANCOVA (adult model 1) included adult Ht, adult Wt, geometric bone measurements at PHV, and sex as covariates to assess differences after controlling for size and adolescent bone geometry. The second ANCOVA (adult model 2) included adult Ht, Wt, geometric bone measurements at PHV, sex, and adult LTM% as covariates to assess differences once relative lean mass was also accounted. Finally, the third ANCOVA (adult model 3) included Ht, Wt, geometric bone measurements at PHV, sex, adult LTM%, and adult PA as covariates to determine the effects of relative muscle mass and current PA levels on adult bone geometry. Pearson correlations were performed to check covariates for collinearity. Covariates that were highly correlated and did not significantly improve the ANCOVA models were excluded from the final analyses. If significant group differences were observed in any models, *post hoc* pairwise

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comparisons with Bonferroni adjustments were used to ascertain individual group differences. All adult covariates were the adult values corresponding to the age at peak bone measure being assessed. For example, in one participant, the age at maximum NN CSA occurred at 7 yr post-PHV (21 yr of age), whereas NN *Z* occurred at 8 yr post-PHV (22 yr of age). Therefore, the adult values for Ht, Wt, LTM%, and PA score at 7 yr post-PHV were used as covariates for NN CSA analyses, whereas values at 8 yr post-PHV were used for NN CSA analyses. Data were checked for normality using skewness and kurtosis. Any violations (skewness or kurtosis values exceeding ±2 times the SE) were adjusted using logarithmic transformations. An alpha of $P < 0.05$ was considered significant. All analyses were performed using Statistical Package for the Social Sciences 20.0 for Windows (SPSS, Chicago, IL).

RESULTS

Adolescent measures. Table 1 provides a summary of the participants' anthropometrics, body composition, and geometric bone measures in adolescence and adulthood. There were no significant differences observed in adolescent age of PHV, Ht, Wt, and LTM% between adolescent PA groups at PHV ($P > 0.05$), but there were significant differences in bone structural strength. Inactive adolescents had significantly lower NN CSA, IT CSA, IT *Z*, S CSA, and S *Z* than their active classified peers at PHV ($P < 0.05$). In addition, the inactive classified individuals had significantly smaller S *Z* than the average active classified individuals ($P < 0.05$, Table 1). No significant differences were observed in absolute adolescent bone geometric measures between average and active participants ($P > 0.05$, Table 1).

TABLE 1. Anthropometrics, body composition, and absolute geometric bone measures in adolescent activity groups at PHV and adulthood.

	Inactive ($n = 31$)	Average ($n = 66$)	Active ($n = 26$)
Values at PHV			
Age of PHV (yr)	12.80 ± 1.12	12.62 ± 1.26	12.46 ± 1.35
Height (cm)	159.74 ± 8.92	159.00 ± 8.84	160.71 ± 5.66
Weight (kg)	45.15 ± 7.68	46.21 ± 9.33	46.83 ± 9.80
Percent LTM	77.28 ± 8.15	76.69 ± 9.33	77.33 ± 7.73
PA score	2.32 ± 0.45	2.98 ± 0.36*	3.54 ± 0.43**
NN CSA (cm^2)	1.69 ± 0.24	1.78 ± 0.32	1.83 ± 0.33*
NN *Z* (cm^3)	0.70 ± 0.16	0.74 ± 0.19	0.77 ± 0.18
IT CSA (cm^2)	3.00 ± 0.46	3.16 ± 0.60	3.31 ± 0.78*
IT *Z* (cm^3)	2.25 ± 0.55	2.41 ± 0.61	2.51 ± 0.64*
S CSA (cm^2)	2.21 ± 0.27	2.29 ± 0.41	2.38 ± 0.48*
S *Z* (cm^3)	1.00 ± 0.20	1.09 ± 0.26*	1.10 ± 0.26*
Adult values			
Age	21.63 ± 2.83	21.97 ± 3.26	21.44 ± 4.11
Height (cm)	174.57 ± 9.58	172.90 ± 9.71	172.65 ± 8.91
Weight(kg)	77.88 ± 17.56	72.26 ± 15.13	74.71 ± 16.27
Percent LTM	66.80 ± 11.47	69.78 ± 10.86	69.64 ± 9.44
PA score	1.91 ± 0.57	2.29 ± 0.54*	2.73 ± 0.43**
PA change	−0.36 ± 0.74	−0.69 ± 0.54	−0.88 ± 0.70*
NN CSA (cm^2)	2.55 ± 0.44	2.61 ± 0.50	2.72 ± 0.60*
NN *Z* (cm^3)	1.21 ± 0.31	1.26 ± 0.37	1.32 ± 0.40
IT CSA (cm^2)	4.25 ± 0.70	4.40 ± 0.85	4.64 ± 1.10*
IT *Z* (cm^3)	3.59 ± 0.83	3.73 ± 1.05	3.95 ± 1.32*
S CSA (cm^2)	3.55 ± 0.68	3.67 ± 0.68	3.80 ± 0.91*
S *Z* (cm^3)	1.83 ± 0.47	1.91 ± 0.45	1.96 ± 0.64

Means ± SD.
*Indicates a significant difference from the inactive adolescent PA group ($P < 0.05$).
**Indicates a significant difference from the inactive and average adolescent PA group ($P < 0.05$).

Adult measures. Comparisons in young adulthood found there were no significant differences in adult anthropometrics or body composition between adult groups classified by adolescent PA levels ($P > 0.05$, Table 1), despite active adolescents maintaining significantly higher levels of self-reported PA in adulthood ($P < 0.05$, Table 1). In addition, significant differences were observed in the reported change in PA from adolescence to adulthood, with individuals classified as active during adolescence having a larger reduction in their self-reported activity levels from adolescence to adulthood compared with those classified as inactive during adolescence (Table 1, $P < 0.05$).

Significant differences in unadjusted bone measures were observed between adolescent PA groups. Inactive classified individuals had significant lower unadjusted NN CSA, IT CSA, IT *Z*, and S CSA than their active adolescent counterparts (Table 1, $P < 0.05$). No significant differences were observed in unadjusted adult bone geometric measures between average and active participants ($P > 0.05$, Table 1).

Adult model 1 (adjustments for height, weight, bone geometry at PHV, and sex). Individuals classified as being inactive during adolescence were observed to have significantly lower adult-adjusted NN CSA (2.57 ± 0.06 vs 2.73 ± 0.07 cm^2), NN *Z* (1.24 ± 0.04 vs 1.33 ± 0.04 cm^3), IT CSA (4.31 ± 0.09 vs 4.60 ± 0.09 cm^2), IT *Z* (3.64 ± 0.10 vs 3.94 ± 0.11 cm^3), S CSA (3.57 ± 0.08 vs 3.74 ± 0.08 cm^2), and S *Z* (1.82 ± 0.05 vs 1.94 ± 0.05 cm^3) than peers classified as active during adolescence ($P < 0.05$); means were adjusted for Ht, Wt, bone geometry at PHV, and sex. In addition, these inactive classified participants had significantly lower adjusted adult IT *Z* (3.64 ± 0.10 vs 3.84 ± 0.07 cm^3), S CSA (3.57 ± 0.08 vs 3.70 ± 0.05 cm^2), and S *Z* (1.82 ± 0.05 vs 1.93 ± 0.03 cm^3) than individuals classified as average active during adolescence ($P < 0.05$); means were adjusted for Ht, Wt, bone geometry at PHV, and sex. There were no significant differences in adjusted adult bone measures between individuals classified as average active and active during adolescence ($P > 0.05$).

For all adult geometric bone measures, Wt and bone geometry significantly contributed to the prediction models, whereas height and sex were also significant predictors for NN *Z*, IT *Z*, S CSA, and S *Z* (Table 2). Model 1 predictors explained between 76% and 83% of the variance in adult bone geometric measures (Table 2).

Adult model 2 (adjustments for height, weight, geometric measure at PHV, sex, and total body lean tissue mass percentage). In model 2, the contribution of relative lean tissue mass was added in the model 1 predictors to assess potential differences once relative muscle mass was also accounted. It was observed that individuals classified as inactive during adolescence had significantly less adult-adjusted NN CSA (2.58 ± 0.06 vs 2.73 ± 0.06 cm^2), NN *Z* (1.25 ± 0.03 vs 1.33 ± 0.04 cm^3), IT CSA (4.32 ± 0.08 vs

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TABLE 2. Beta coefficients and model variances for the ANCOVA.

	Adjusted R^2	Height	Weight	Adolescent Geometry	Sex	Lean Tissue Mass	Adult PA
Model 1[a]							
NN CSA	0.76	0.006 ± 0.004	0.007 ± 0.002*	1.08 ± 0.13*	−0.077 ± 0.090	Not applicable	Not applicable
NN *Z*	0.79	0.007 ± 0.003*	0.005 ± 0.002*	1.21 ± 0.16*	−0.140 ± 0.058*		
IT CSA	0.82	0.010 ± 0.006	0.010 ± 0.003*	1.07 ± 0.09*	−0.159 ± 0.139		
IT *Z*	0.83	0.035 ± 0.008*	0.012 ± 0.004*	0.97 ± 0.12*	−0.462 ± 0.146*		
S CSA	0.80	0.015 ± 0.005*	0.015 ± 0.003*	0.98 ± 0.12*	−0.218 ± 0.113*		
S *Z*	0.82	0.015 ± 0.003*	0.009 ± 0.002*	0.83 ± 0.13*	−0.134 ± 0.066*		
Model 2[b]							
NN CSA	0.77	−0.001 ± 0.006	0.003 ± 0.003	1.01 ± 0.13*	0.124 ± 0.126	0.012 ± 0.005*	Not applicable
NN *Z*	0.84	−0.002 ± 0.003	0.000 ± 0.002	1.04 ± 0.15*	0.057 ± 0.077	0.015 ± 0.003*	
IT CSA	0.83	−0.004 ± 0.008	0.002 ± 0.004	0.99 ± 0.10*	0.99 ± 0.10*	0.021 ± 0.008*	
IT *Z*	0.85	0.015 ± 0.009	0.001 ± 0.005	0.86 ± 0.11*	−0.211 ± 0.205	0.032 ± 0.009*	
S CSA	0.84	−0.007 ± 0.006	0.005 ± 0.003	0.83 ± 0.11*	0.259 ± 0.143	0.031 ± 0.007*	
S *Z*	0.87	0.001 ± 0.004	0.002 ± 0.002	0.74 ± 0.11*	0.190 ± 0.082*	0.020 ± 0.004*	
Model 3[c]							
NN CSA	0.78	−0.030 ± 0.005	0.001 ± 0.003	1.10 ± 0.13*	0.180 ± 0.120	0.013 ± 0.005*	0.0004 ± 0.047*
NN *Z*	0.85	−0.002 ± 0.003	0.000 ± 0.002	1.02 ± 0.15*	0.073 ± 0.076	0.015 ± 0.003*	0.023 ± 0.028*
IT CSA	0.84	−0.001 ± 0.008	0.002 ± 0.005	0.97 ± 0.10*	0.105 ± 0.192	0.022 ± 0.009*	0.038 ± 0.069*
IT *Z*	0.86	0.015 ± 0.009	0.001 ± 0.005	0.86 ± 0.11*	−0.240 ± 0.210	0.032 ± 0.009*	0.030 ± 0.075*
S CSA	0.86	−0.007 ± 0.006	0.005 ± 0.004	0.83 ± 0.11*	0.279 ± 0.144	0.030 ± 0.007*	0.063 ± 0.060*
S *Z*	0.87	0.001 ± 0.004	0.001 ± 0.002	0.76 ± 0.11*	0.199 ± 0.082*	0.021 ± 0.004*	0.014 ± 0.030

Beta coefficients ± SE.
[a]Model included height, weight bone geometry at PHV, and sex as covariates.
[b]Model included weight, bone geometry at PHV, sex, and total body lean tissue mass percentage as covariates.
[c]Model included weight, bone geometry at PHV, sex, total body lean tissue mass percentage, and adult PA as covariates.
*Indicates covariate is significant ($P < 0.05$).

4.60 ± 0.10 cm^2), IT *Z* (3.66 ± 0.09 vs 3.95 ± 0.10 cm^3), S CSA (3.60 ± 0.09 vs 3.75 ± 0.07 cm^2), and S *Z* (1.84 ± 0.04 vs 1.93 ± 0.04 cm^2) than those individuals described as being active during adolescence ($P < 0.05$); means were adjusted for Ht, Wt, bone geometry at PHV, sex, and lean tissue mass percentage. In addition, individuals described as average active during adolescence had significantly less adult-adjusted IT CSA (4.32 ± 0.08 vs 4.60 ± 0.10 cm^2) compared with the adolescent active counterparts ($P < 0.05$); means were adjusted for Ht, Wt, bone geometry at PHV, sex, and lean tissue mass percentage. No significant differences in the other adjusted adult bone measures were observed between individuals classified as average active and active during adolescence ($P > 0.05$). Similarly, no significant differences in the adjusted adult bone measures were seen between individuals classified as inactive and average active during adolescence ($P > 0.05$).

For all adult geometric bone measures, adolescent bone geometry and lean tissue mass percentage significantly contributed to the prediction models, whereas sex also contributed significantly as a predictor for S *Z* (Table 2). Model 2 predictors explained between 77% and 87% of the variance in adult bone geometric measures (Table 2).

Adult model 3 (adjustments for weight, geometric measure at PHV, sex, total body lean tissue mass percentage, and adult PA). In model 3, the contribution of adult PA was added to the model 2 predictors to assess potential differences once current activity levels were adjusted. Figures 1–3 display the adult-adjusted means for geometric bone measures and the NN, IT, and S sites of the

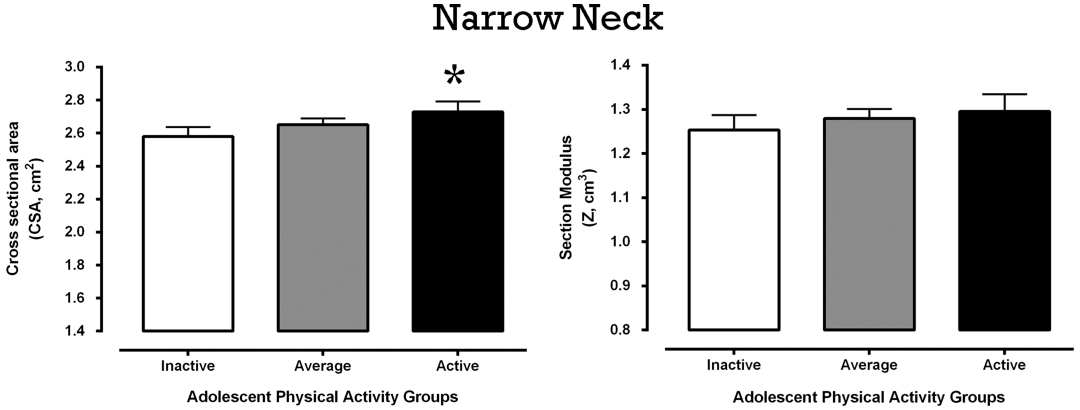

FIGURE 1—Model 3 adjusted adult geometric bone measures at the NN site of the proximal femur for individuals classified by adolescent PA. Means adjusted for weight, adolescent bone geometry, sex, total body lean tissue mass percentage, and adult PA. Adjusted means ± SE. *Indicates a significant difference from the inactive PA group ($P < 0.05$).

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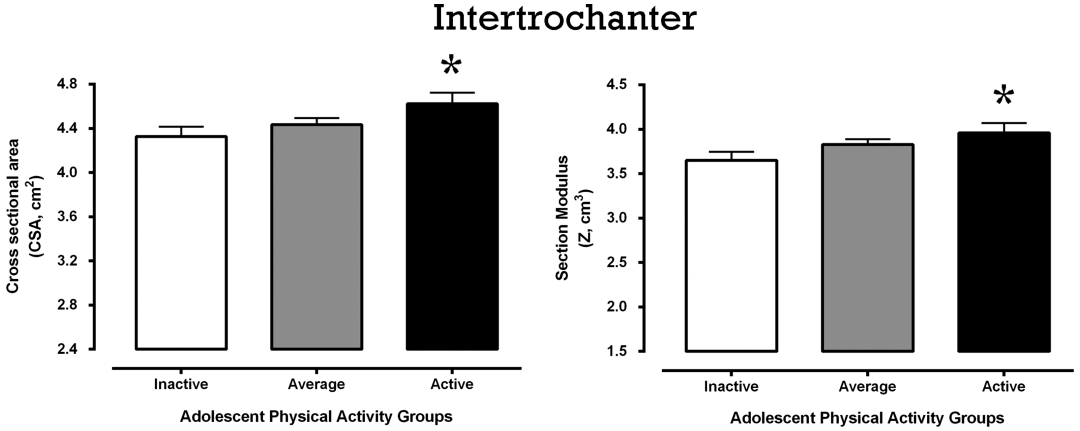

FIGURE 2—Model 3 adjusted adult geometric bone measures at the IT site of the proximal femur for individuals classified by adolescent PA. Means adjusted for weight, adolescent bone geometry, sex, total body lean tissue mass percentage, and adult PA. Adjusted means ± SE. *Indicates a significant difference from the inactive PA group ($P < 0.05$).

proximal femur, respectively. Individuals classified as inactive during adolescence had significantly less NN CSA, IT CSA, IT *Z*, and S *Z* than individuals classified as active adolescents ($P < 0.05$, Figures 1–3); means were adjusted for Ht, Wt, bone geometry at PHV, sex, lean tissue mass percentage, and adult PA levels. These inactive individuals also had significantly less adult-adjusted S *Z* than those individuals classified as average active during adolescence ($P < 0.05$, Fig. 3); means were adjusted for Ht, Wt, bone geometry at PHV, sex, lean tissue mass percentage, and adult PA levels. No significant differences were observed in any adult-adjusted bone geometric measure between individuals classified as average active and inactive during adolescence ($P > 0.05$, Figs. 1–3).

Adolescent bone geometry and lean tissue mass percentage significantly contributed to the prediction models of all geometric bone measures, whereas adult PA also contributed significantly as a predictor to all bone measures except S *Z* (Table 2). Sex was only a significant predictor of S *Z* (Table 2). Model 3 predictors explained between 78% and 87% of the variance in adult bone geometric measures (Table 2).

DISCUSSION

The aim of the present study was to investigate if the positive effects of PA on bone strength during adolescence were still present in young adulthood. It was observed that PA during adolescence was positively related with estimated adolescent bone CSA and section modulus at the proximal femur and that these advantages persisted into early adulthood even after current adult levels of PA were accounted. This is the first study, to our knowledge, to assess the relationship between adolescent PA and adult geometric bone strength measures in a healthy nonathlete specific cohort at the clinically relevant proximal femur using a longitudinal data set.

According to the mechanostat theory (21), PA provides novel dynamic loads that can elicit adaptations to bone mass,

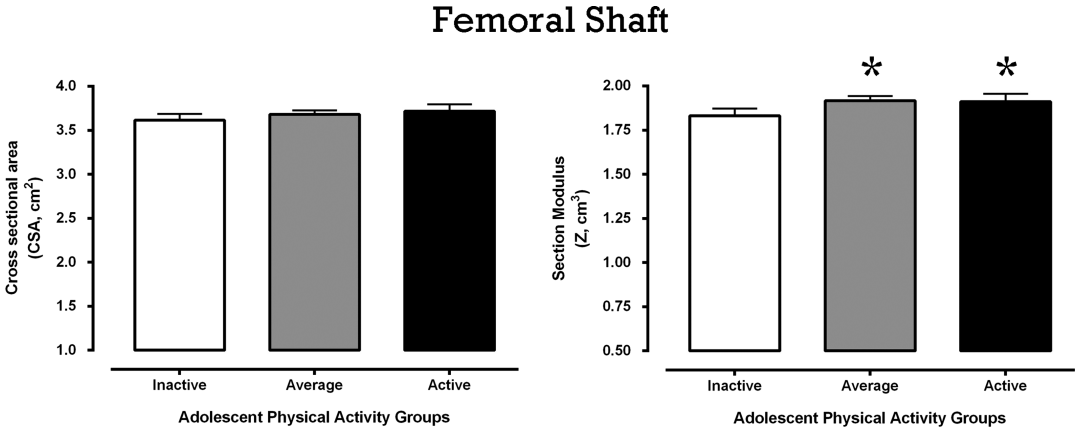

FIGURE 3—Model 3 adjusted adult geometric bone measures at the shaft (S) site of the proximal femur for individuals classified by adolescent PA. Means adjusted for weight, adolescent bone geometry, sex, total body lean tissue mass percentage, and adult PA. Adjusted means ± SE. *Indicates a significant difference from the inactive PA group ($P < 0.05$).

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geometry, and architecture. In the present study, it was observed that, around the time of peak statural growth (PHV), active adolescents had 8%–12% greater CSA and 9%–12% greater *Z* than their inactive peers at the proximal femur. These adolescent findings parallel those previously reported for adolescent BMC and bone geometry in the same cohort (5,20), and further support the conjecture that childhood and adolescence PA is positively associated with adolescent CSA and *Z* at the proximal femur in both sexes. Although the current adolescent findings reported in this article reinforce the positive relationship between PA and adolescent bone strength, this was not the main purpose of the current study. The purpose was to investigate whether these adolescent benefits were maintained into young adulthood, when the peak in proximal femur CSA and *Z* has been identified to occur (23). When adult CSA and *Z* were adjusted for height, weight, adolescent bone geometry, and sex, individuals identified as active during adolescence maintained a 5%–7% benefit in CSA and 6%–8% benefit in *Z* in adulthood compared with their inactive adolescent counterparts. These findings suggest that the skeletal benefits of adolescent PA on adolescent CSA and *Z* at the proximal femur are maintained into adulthood, supporting conclusions drawn from other estimates of bone strength (5,18,33).

The previous conclusion, however, ignores the potential role of muscle strength on geometric bone structural strength. Given that lean tissue mass, a surrogate of muscle strength, has positive effects on geometric bone strength measures (15,22,35,36), ignoring this connection may result in spurious conclusions. To address this concern, relative lean tissue mass was included as a covariate in model 2, alongside model 1 predictors. It was observed that when relative lean tissue mass was accounted, active individuals continued to maintain between 4% and 7% greater benefits in CSA and a 5% to 8% advantages in *Z* over their inactive peers. These findings would suggest that adolescent activity provides skeletal advantages to adult CSA and *Z* at the proximal femur beyond relative adult muscle mass.

PA is also widely documented to have positive effects, independent of lean tissue mass, on bone geometry throughout life (20). When adult PA was included as an additional covariate in model 3 (Table 2 and Figs. 1–3), those active adolescents still maintained, although slightly reduced, a 3%–7% benefit to adult CSA and a 3%–8% benefit to adult *Z*. Given the CSA and *Z* direct inverse relationships with compressive and bending stress, these benefits would translate to a 3%–8% reduction in the compressive and bending stresses experienced at the proximal femur. These findings are comparable with those published in recent athlete models that have documented sustained skeletal advantages from high levels of early life PA on adult bone mass, geometry, and architecture (16,18,19,33,38). Erlandson et al. (18) reported that retired gymnasts accrued between 3% and 7% greater BMC at the total body and femoral neck compared with gymnastic controls, whereas Pollock et al. (33) observed an 8%–14% advantage in adult aBMD at the total boy, lumbar spine, proximal femur, and femoral neck in former college gymnasts. Similarly, Eser et al. (19), using pQCT, described retired athletes to maintain 2%–11% greater total CSA at the femur compared with nonathletic controls. Although these studies focused on athletes who have been training during childhood and adolescence, the current findings suggest that habitual PA in adolescence, in nonathlete-specific population, may also be similarly advantageous to adult geometric bone strength. Thus, the early implementation of habitual PA during adolescence may provide lifelong benefits to adult skeletal health and fracture prevention.

When assessing the independent contribution of height, weight, adolescent bone geometry, sex, relative LTM, and current adult PA levels, it was apparent in model 3 that only adolescent bone geometry, relative LTM, and current adult PA were significant independent predictors of adult geometric bone strength. Height and weight were excluded as predictors once relative LTM was included in the models. This was not surprising given the strong correlation between height, weight, and relative LTM. The independent contribution of relative LTM as a predictor further supports the extensive amount of literature highlighting the strong muscle–bone relationship. LTM, a surrogate of muscle strength, is well documented to provide physiological strains directly to the bone because the muscles act as inefficient levers arms during daily movement and locomotion. In addition, LTM serves to provide additional body mass, which increase gravitational loads, resulting in greater axial compression and bending forces experienced at weight bearing regions, such as the proximal femur (8). Similarly, adult PA levels were observed to be an independent predictor of adult geometric bone strength. Although the inclusion of adult PA to the models provided modest improvements (1%–2%, Table 2) to the prediction of adult geometric measures, its significant inclusion highlights the importance of current activity levels on geometric bone strength. These modest alterations to the prediction models may be due to the acknowledged positive relationship between PA and LTM (3). Alternatively, assessing the type of activity engaged in may provide enhanced understanding of the contribution of PA to geometric bone strength. High-impact and odd-impact loading activities (i.e., gymnastics, soccer, and hockey) have been associated with higher aBMD and enhanced bone geometry at regions specific to the loading pattern, whereas low-impact/nonimpact activities (i.e., swimming and cycling) are associated with greater aBMD but reduced hip geometric measures (41). These high-impact weight-bearing activities are ideal for bone adaptation because they produce novel and dynamic strains on the bony tissue (21); thus, these activities may better reflect the independent contributions of PA on skeletal strength in adulthood. Given that the PAQ used in the current study was not designed to capture the type of activity or localized loading associated with specific types of activity, future research that discriminates between the type, amount, and maintenance of activity is necessary to identify their independent roles of PA and LTM on the development

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and transfer of geometric bone properties from adolescence to adulthood.

Despite the unique longitudinal data, the prospectively determined PA levels, and careful control of potential confounding variables, the conclusions of the present study are limited by several factors. First, this is an observational study, susceptible to observational associations that may be related to uncontrolled factors such as selection bias and reverse causality. Also, because the PBMAS is drawn from a small cohort of regionally selected Caucasian adolescents, the present observations and conclusions may have limited application to other cohorts. Further longitudinal research in other populations is required to supplement these observations. Next, PA was assessed using a subjective questionnaire. Although the PAQ is a reliable and valid method for assessing PA in children, adolescents, and adults (13,24,29), it provides little information on discriminating the nature of the activity. As a result, the observations of this study are unable to suggest what type, frequency, and duration of adolescent physical is ideal to maintain skeletal benefits in adulthood. Instead, future studies using bone-specific measures, such as the bone-specific PA questionnaire (43) or objective measures of PA, which provide greater sensitivity to categorizing activity and loading type, would supplement the present study findings. Nutritional intake also plays a vital role in developing bone structural strength. Although the PBMAS has collected calcium intake by 24-h food recall, the inclusion of these data did not significantly alter the current findings (data not shown). Further investigations with more sensitive nutritional assessments are warranted to confirm the present observations. Finally, the geometric bone measures were derived using HSA. Although HSA geometric measures have been validated against other three dimensional assessment techniques (34), the HSA geometric measures are derived using noisy two-dimensional DXA images, which may hinder the detection of precise edge margins (9). In addition, the position of femur is important because small changes in femur rotation have a large effect on the geometric dimensions (9). All DXA scans were performed by qualified technicians familiar with proper positioning of the proximal femur to ensure hip scans were performed with care to limit these potential errors; nevertheless, it is difficult to position the hip consistently in repeated measures over time. Also, HSA-derived CSA and *Z* are not clinically measures for assessing osteoporosis or fracture risk; thus, the clinical application of these observations remains equivocal. Regardless of the HSA's inherent limitations, it remains one of the few modalities that is safe, easy, and cost-effective in assessing the geometry of the proximal femur. Despite these limitations, the current study provides novel information surrounding the relationship between adolescent PA and adult bone geometric properties at the proximal in males and females.

In conclusion, being active during adolescence provides skeletal advantages to adolescent geometric bone strength, which appear to be maintained into adulthood even when adjusted for key confounding variables such as body composition and current activity levels. Thus, the promotion of PA during adolescence and adulthood is recommended as a strategy for maintaining life-long skeletal health and reducing fracture risk.

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REFERENCES

1. Bailey DA, McKay HA, Mirwald RL, Crocker PR, Faulkner RA. A six-year longitudinal study of the relationship of physical activity to bone mineral accrual in growing children: the university of Saskatchewan bone mineral accrual study. *J Bone Miner Res*. 1999; 14(10):1672–9.
2. Bass SL, Saxon L, Daly RM, et al. The effect of mechanical loading on the size and shape of bone in pre-, peri-, and postpubertal girls: a study in tennis players. *J Bone Miner Res*. 2002;17(12):2274–80.
3. Baxter-Jones AD, Eisenmann JC, Mirwald RL, Faulkner RA, Bailey DA. The influence of physical activity on lean mass accrual during adolescence: a longitudinal analysis. *J Appl Physiol*. 2008; 105:734–41.
4. Baxter-Jones AD, Faulkner RA, Forwood MR, Mirwald RL, Bailey DA. Bone mineral accrual from 8 to 30 years of age: an estimation of peak bone mass. *J Bone Miner Res*. 2011;26(8): 1729–39.
5. Baxter-Jones AD, Kontulainen SA, Faulkner RA, Bailey DA. A longitudinal study of the relationship of physical activity to bone mineral accrual from adolescence to young adulthood. *Bone*. 2008; 43(6):1101–7.
6. Baxter-Jones AD, Mirwald RL, McKay HA, Bailey DA. A longitudinal analysis of sex differences in bone mineral accrual in healthy 8–19-year-old boys and girls. *Ann Hum Biol*. 2003;30(2): 160–75.
7. Baxter-Jones AD, Sherar LB. Growth and maturation. In: Armstrong N, editor. *Pediatric Exercise Physiology*. Edinburgh: Elsevier Limited; 2006. p. 1–26.
8. Beck BR. Muscle forces or gravity—what predominates mechanical loading on bone? Introduction. *Med Sci Sports Exerc*. 2009;4(11): 2033–6.
9. Beck T. Measuring the structural strength of bones with dual-energy X-ray absorptiometry: principles, technical limitations, and future possibilities. *Osteoporos Int*. 2003;14(S5):81–8.
10. Beck TJ, Ruff CB, Warden KE, Scott WW Jr, Rao GU. Predicting femoral neck strength from bone mineral data. A structural approach. *Invest Radiol*. 1990;25(1):6–18.
11. Belavy DL, Beller G, Ritter Z, Felsenberg D. Bone structure and density via HR-pQCT in 60d bed-rest, 2-years recovery with and without countermeasures. *J Musculoskelet Neuronal Interact*. 2011; 11:(3): 215–26.
12. Ceroni D, Martin X, Delhumeau C, Rizzoli R, Kaelin A, Farpour-Lambert N. Effects of cast-mediated immobilization on bone mineral mass at various sites in adolescents with lower-extremity fracture. *J Bone Joint Surg Am*. 2012;94(3):208–16.

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13. Copeland J, Kowalski KC, Donen RM, Tremblay MS. Convergent validity of the physical activity questionnaire for adults: the new member of the PAQ family. *J Phys Act Health*. 2005;2:216–29.
14. Daly RM. The effect of exercise on bone mass and structural geometry during growth. In: Borms J, Hebbelinck M, Hills AP, editors. *Optimizing Bone Mass and Strength. The Role of Physical Activity and Nutrition during Growth*. Farmington, CT: Karger: 2007, p. 33–49.
15. Daly RM, Stenevi-Lundgren S, Linden C, Karlsson MK. Muscle determinants of bone mass, geometry and strength in prepubertal girls. *Med Sci Sports Exerc*. 2008;40(6):1135–41.
16. Ducher G, Hill BL, Angeli T, Bass SL, Eser P. Comparison of pQCT parameters between ulna and radius in retired elite gymnasts: the skeletal benefits associated with long-term gymnastics are bone- and site-specific. *J Musculoskelet Neuronal Interact*. 2009;9(4):247–55.
17. Duckham R, Baxter-Jones AD, Johnston JD, Vatanparast H, Cooper DM, Kontulainen SA. Does physical activity in adolescence have site-specific and sex-specific benefits on young adult bone size, content and estimated strength? *J Bone Miner Res*. 2014;29(2):479–86.
18. Erlandson M, Kontulainen S, Chilibeck P, Arnold C, Faulkner R, Baxter-Jones A. Higher premenarcheal bone mass in elite gymnasts is maintained into young adulthood after long-term retirement from sport: a 14-year follow-up. *J Bone Miner Res*. 2012; 27(1):104–10.
19. Eser P, Hill B, Ducher G, Bass S. Skeletal benefits after long-term retirement in former elite female gymnasts. *J Bone Miner Res*. 2009; 24(12):1981–8.
20. Forwood MR, Baxter-Jones AD, Beck TJ, Mirwald RL, Howard A, Bailey DA. Physical activity and strength of the femoral neck during the adolescent growth spurt: a longitudinal analysis. *Bone*. 2006;38(4):576–83.
21. Frost HM. Bone's mechanostat: a 2003 update. *Anat Rec A Discov Mol Cell Evol Biol*. 2003;275(2):1081–101.
22. Jackowski SA, Faulkner RA, Farthing JP, Kontulainen SA, Beck TJ, Baxter-Jones AD. Peak lean tissue mass accrual precedes changes in bone strength indices at the proximal femur during the pubertal growth spurt. *Bone*. 2009;44(6):1186–90.
23. Jackowski SA, Kontulainen SA, Cooper DM, Lanovaz JL, Jones AD. The timing of bone mineral density and geometric adaptation at the proximal femur from childhood to early adulthood in males and females: a longitudinal study. *J Bone Miner Res*. 2011;26(11): 2753–61.
24. Janz KF, Lutuchy EM, Wenthe P, Levy SM. Measuring activity in children and adolescents using self-report: PAQ-C and PAQ-A. *Med Sci Sports Exerc*. 2008;40(4):767–72.
25. Kannus P. Preventing osteoporosis, falls, and fractures among elderly people. Promotion of lifelong physical activity is essential. *BMJ*. 1999; 318(7178):205–6.
26. Kaptoge S, Beck TJ, Reeve J, et al. Prediction of incident hip fracture risk by femur geometry variables measured by hip structural analysis in the study of osteoporotic fractures. *J Bone Miner Res*. 2008;23(12):1892–904.
27. Khoo BC, Beck TJ, Qiao QH, et al. In vivo short-term precision of hip structure analysis variables in comparison with bone mineral density using paired dual-energy X-ray absorptiometry scans from multi-center clinical trials. *Bone*. 2005;37(1):112–21.
28. Kontulainen S, Sievanen H, Kannus P, Pasanen M, Vuori I. Effect of long-term impact-loading on mass, size, and estimated strength of humerus and radius of female racquet-sports players: a peripheral quantitative computed tomography study between young and old starters and controls. *J Bone Miner Res*. 2003; 18(2):352–9.
29. Kowalski KC, Crocker PR, Kowalski N. Convergent validity of the physical activity questionnaire for adolescence. *Pediatr Exerc Sci*. 1997;9:342–53.
30. 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):919–29.
31. Martin RB, Burr DB. Non-invasive measurement of long bone cross-sectional moment of inertia by photon absorptiometry. *J Biomech*. 1984;17(3):195–201.
32. Papaioannou A, Kennedy CC, Ioannidis G, et al. The impact of incident fractures on health-related quality of life: 5 years of data from the Canadian Multicentre Osteoporosis Study. *Osteoporos Int*. 2009;20(5):703–14.
33. Pollock NK, Laing EM, Modlesky CM, O'Connor PJ, Lewis RD. Former college artistic gymnasts maintain higher BMD: a nine-year follow-up. *Osteoporos Int*. 2006;17(11):1691–7.
34. Ramamurthi K, Ahmad O, Engelke K, et al. An in vivo comparison of hip structure analysis (HSA) with measurements obtained by QCT. *Osteoporos Int*. 2012;23(2):543–51.
35. Rauch F, Bailey DA, Baxter-Jones A, Mirwald R, Faulkner R. The 'muscle–bone unit' during the pubertal growth spurt. *Bone*. 2004; 34(5):771–5.
36. Robling AG. Is bone's response to mechanical signals dominated by muscle forces? *Med Sci Sports Exerc*. 2009;41(11):2044–9.
37. Ross W, Marfell-Jones M. Kinanthropometry. In: H Green, editor. *Physiological Testing of the High Performance Athlete*. Champaign (IL): Human Kinetics; 1991. p. 223–307.
38. Scerpella TA, Dowthwaite JN, Rosenbaum PF. Sustained skeletal benefit from childhood mechanical loading. *Osteoporos Int*. 2010; 22(7):2205–10.
39. Sherar LB, Esliger DW, Baxter-Jones AD, Tremblay MS. Age and gender differences in youth physical activity: does physical maturity matter? *Med Sci Sports Exerc*. 2007;39(5):830–5.
40. Sievanen H. Immobilization and bone structure in humans. *Arch Biochem Biophys*. 2010;503(1):146–52.
41. Tenforde AS, Fredericson M. Influence of sports participation on bone health in the young athlete: a review of the literature. *PM R*. 2011;3(9):861–7.
42. Wang QJ, Suominen H, Nicholson PH, et al. Influence of physical activity and maturation status on bone mass and geometry in early pubertal girls. *Scand J Med Sci Sports*. 2005;15(2):100–6.
43. Weeks BK, Beck BR. The BPAQ: a bone-specific physical activity assessment instrument. *Osteoporos Int*. 2008;19(11):1567–77.

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