Published in final edited form as:

Osteoporos Int. 2011 May ; 22(5): 1419–1430. doi:10.1007/s00198-010-1361-8.

Associations of physical activity duration, frequency, and load with volumetric BMD, geometry, and bone strength in young girls

Joshua N. Farr¹, Robert M. Blew¹, Vinson R. Lee¹, Timothy G. Lohman¹, and Scott B. Going²

¹Department of Physiological Sciences, University of Arizona, Tucson, AZ, USA

²Department of Nutritional Sciences, University of Arizona, Tucson, AZ, USA

Abstract

Purpose—This study evaluated the associations of physical activity (PA) duration, frequency, load, and their interaction (total PA score = duration × frequency × load) with volumetric bone mineral density, geometry, and indices of bone strength in young girls.

Methods—465 girls (aged 8–13 years) completed a past year physical activity questionnaire (PYPAQ) which inquires about the frequency (days/week) and duration (average minutes/session) of leisure-time PA and sports. Load (peak strain score) values were assigned to each activity based on ground reaction forces. Peripheral quantitative computed tomography was used to assess bone parameters at metaphyseal and diaphyseal sites of the femur and tibia of the non-dominant leg.

Results—Correlations across all skeletal sites between PA duration, frequency, load and periosteal circumference (PC), bone strength index (BSI), and strength-strain index (SSI) were significant ($p \leq 0.05$), although low (0.10–0.17). A 2.7–3.7% greater PC across all skeletal sites was associated with a high compared to a low PYPAQ score. Also, a high PYPAQ score was associated with greater BSI (6.5–8.7%) at metaphyseal sites and SSI (7.5–8.1%) at diaphyseal sites of the femur and tibia. The effect of a low PYPAQ score on bone geometric parameters and strength was greater than a high PYPAQ score.

Conclusions—PA duration, frequency, and load were all associated with bone geometry and strength, although their independent influences were modest and site specific. Low levels of PA may compromise bone development whereas high levels have only a small benefit over more average levels.

Keywords

Exercise; Female; Youth; Bone geometry; Peripheral quantitative computed tomography (pQCT)

Introduction

Osteoporosis, a major global public health concern, is characterized by microarchitectural deterioration and loss of bone tissue that consequently increases susceptibility to fracture [1]. Although historically considered a disease of the elderly, there is now considerable

Corresponding author: J.N. Farr, M.S. Department of Physiological Sciences The University of Arizona 1713 E. University Blvd. #93 Tucson, AZ, USA 85721-0093 Phone: 520-444-5881 Fax: 520-621-8170 jfarr@email.arizona.edu.

Author emails: Joshua N. Farr (jfarr@email.arizona.edu) Robert M. Blew (rblew@email.arizona.edu) Vinson R. Lee (vinsonl@email.arizona.edu) Timothy G. Lohman (lohman@email.arizona.edu) Scott B. Going (going@email.arizona.edu)

CONFLICTS OF INTEREST: NONE

agreement that osteoporosis is a condition with origins in childhood and adolescence [2]. While skeletal development is largely determined by heritable factors [3], modifiable factors can also compromise or enhance bone acquisition. Since >90% of adult skeletal mass is acquired during childhood and adolescence [2], one strategy aimed to reduce the risk of fracture is to optimize bone parameters that determine bone strength. This could be achieved via exercise-induced adaptations in volumetric bone mineral density (vBMD, mg/cm³) or bone geometry during growth. The optimal type and amount of physical activity (PA) needed to induce bone adaptations during growth remain unclear. Such information would be useful in the development of bone health recommendations for youth and should underlie the design of exercise interventions aimed to optimize bone strength.

Controlled loading studies in animals have identified key features of osteogenic stimuli such as increased strain magnitude [4, 5] and frequency [6] within a safe range. Increased duration (e.g., increased number of loading cycles) may also be an important osteogenic stimulus as long as the distribution of strain is altered throughout the loading session [7]. Unfortunately, highly controlled studies in children and adults, in which components of activity dose are manipulated, are few and difficult to conduct. While observational studies might also address this issue, studies of the association of PA with bone typically only examine the influence of total activity and not its components (e.g., duration, frequency, load), in part, because standardized methods for capturing the bone-relevant components of PA in humans are lacking.

We recently developed and tested a questionnaire for assessing bone loading activities in youth [8]. Using that questionnaire in the present study, we sought to determine whether any individual component of PA (duration, frequency, load) or their interaction (duration × frequency × load) was associated with vBMD, geometry, and indices of bone strength in young girls, aged 8–13 years. A unique feature was the use of peripheral quantitative computed tomography (pQCT) for assessment of bone geometry and vBMD. The mechanical strength of bone is determined both by its material properties (e.g., vBMD) and its structural properties (e.g., geometry) [9]. In addition to increased mineralization, small changes in the shape of bone (e.g. an increase in the outer circumference) can dramatically increase bone strength and fracture resistance [10]. Past reliance on dual-energy X-ray absorptiometry (DXA) and so-called areal BMD (aBMD, g/cm²), which does not adjust for the depth of bone or provide direct measures of bone geometry, has confounded our understanding of the relationship between PA and bone parameters. Considering the findings from animal studies [4–6], we hypothesized that PA load (peak strain score) and frequency (days/week) would be more strongly associated with bone parameters than increased duration (minutes/session) of PA.

Methods

Participants

The study population has been described previously [11]. Data reported in this paper are from the baseline assessments. The sample included 465 healthy girls, aged 8–13, who were participants in the “Jump-In: Building Better Bones” study. The long-term goal of the Jump-In study is to prospectively assess the effects of high-impact jumping exercises on bone macro-architecture in pre- and early-pubertal girls. Girls who were in school grade 4 or 6 were recruited from 14 elementary and 4 middle schools around Tucson, Arizona. Exclusion criteria included learning disabilities (identified by schools) that made it impossible to complete questionnaires or otherwise unable to comply with assessment protocols; medications, medical conditions, or a disability that limited participation in physical exercise as defined by the Committee on Sports Medicine and Fitness [12]; excluded (or excused) from participation in physical education; and the inability to read and understand English.

The protocol was approved by the University of Arizona Human Subjects Protection Committee and the study was conducted in accordance with the Helsinki Declaration. All guardians and girls provided written informed consent. Guardians completed a health history questionnaire with questions on participant ethnicity and race.

Anthropometry

Anthropometric measures were obtained following standardized protocols [13]. Body mass was measured to the nearest 0.1 kg using a calibrated scale (Seca, Model 881, Hamburg, Germany) and height and sitting height were measured at full inhalation to the nearest mm using a stadiometer (Shorr Height Measuring Board, Olney, MD). Non-dominant femur length (nearest mm) was measured from the base of the patella to the inguinal crease. Non-dominant tibia length (nearest mm) was measured from the proximal end of the medial border of the tibial plateau to the distal edge of the medial malleolus. Coefficients of variation (CVs) for femur and tibia lengths were 0.33% and 0.51%, respectively (n = 465).

Physical Maturation

Maturity was assessed from self-report (with assistance available) of breast development based on Tanner stages [14]. The questionnaire presents illustrations of stages of development, and has been shown to agree with physician exam and grading [15]. Although Tanner staging is common in developmental studies, its ability to accurately assess maturation may be limited [16]. Consequently, we also assessed years from peak height velocity (PHV), an index of maturation, estimated using Mirwald's equation [17] derived from a six-year longitudinal study in boys and girls [18]. In Mirwald's sample, the algorithm for girls was reported to explain 89% of the variance in years from PHV [17].

Past year physical activity questionnaire (PYPAQ)

The past year physical activity questionnaire (PYPAQ) has been validated in adolescents [19]. We modified the questionnaire to include a more comprehensive list of 41 activities common to youth [8], and used the modified PYPAQ to survey all sport and leisure-time PA in which subjects had engaged at least 10 times in the past year outside of physical education class. The questionnaire was administered in an interview with the subject and guardian(s). Participants were asked to record average duration, weekly frequency, and the number of months of participation for each activity. Total PYPAQ score was computed using a modified equation from Shedd et al. [20]: $\text{PYPAQ score} = \sum_{i=1}^n (\text{duration (average minutes/session)} \times \text{frequency (months/12)} \times \text{days/week} \times \text{load (peak strain score)})$, where n was the number of activities a subject reported during the past year. Individual scores for PA duration, frequency, and load were calculated using the following equations: $\text{Duration} = \sum_{i=1}^n (\text{average minutes/session})$; $\text{Frequency} = \sum_{i=1}^n (\text{months/12} \times \text{days/week})$; $\text{Load} = \sum_{i=1}^n (\text{peak strain score})$, where n was the number of activities a subject reported during the past year. PA intensity, commonly reported as the metabolic equivalent (MET, where 1 MET = $3.5 \text{ mL} \times \text{kg}^{-1} \times \text{min}^{-1}$) value of an activity [21], was not included in the PYPAQ equation to protect against colinearity because intensity and load were highly correlated ($r = 0.94$), and because peak strain is more relevant to bone than METs. Peak strain scores (PSS) reported by Groothausen et al. [22] were used to increase the contribution of bone-relevant loading activities to the overall score. Jumping activities (e.g., basketball, gymnastics, volleyball) were assigned a PSS of 3; activities that involve changing directions quickly and sprinting (e.g., soccer, tennis) were assigned a PSS of 2; all other weight-bearing activities were assigned a PSS of 1 (e.g., golf, hiking, walking). Low-impact activities that fell between categories were given a PSS of 1.5 (e.g., aerobics, dance). Non-weight-bearing physical activities (e.g. swimming, cycling) were assigned a PSS of 0.5. Sports and leisure-time activities that did not have a PSS previously reported in the literature were assigned the same value as the most similar activity.

Bone and body composition assessment

Bone geometry and vBMD were assessed at the distal 4% and 20% femur and 4% and 66% tibia sites of the non-dominant leg using pQCT (XCT 3000; STRATEC Medizintechnik GmbH, Pforzheim, Germany, Division of Orthometrix; White Plains, NY). Subjects were asked with which foot they would kick a ball when playing soccer/kickball. If the subject was uncertain, she was asked with what hand she writes and that was determined to be her side of dominance. Scout scans were performed to locate the distal growth plates, with the scanner programmed to subsequently find the sites of interest. pQCT scans were analyzed using Stratec software, Version 5.50. At the distal metaphyseal sites of the femur and tibia, we used Contour mode 3 (169 mg/cm³) to define the total bone and Peel mode 4 (650 mg/cm³ with a 10% peel) was used to ensure that only trabecular bone remained. At the diaphyseal 20% femur and 66% tibia sites, Contour mode 1 (710 mg/cm³), Peel mode 2 (710 mg/cm³), and Cort mode 2 (710 mg/cm³) were used. Further details on image processing, calculations (e.g., bone strength indices), and analysis, including descriptions of Contour, Peel, and Cort modes are published elsewhere [23]. Slice thicknesses were 2.3 mm and voxel sizes were set at 0.4 mm for all sites. Scanner speed was set at 25 mm/second. Trabecular vBMD (mg/cm³), periosteal circumference (PC, mm), and bone strength index (BSI, mg²/mm⁴), calculated as described by Kontulainen [24], were assessed at the 4% distal femur and tibia. At the 20% femur and 66% tibia, cortical vBMD (mg/cm³), cortical area (mm²), endosteal circumference (EC, mm), PC, cortical thickness (mm), and strength-strain index (SSI, mm³), calculated as described by Shedd [20], were assessed. BSI estimates the bone's ability to withstand compression at metaphyseal sites, while SSI is used to estimate the bone's ability to resist torsion and bending forces at diaphyseal sites. Because of the difficulties in interpreting metaphyseal bone density measurements from a single slice [25], we averaged 3 pQCT slices at both the femur and tibia 4% sites. Operators were trained on pQCT scanning and software analyses following guidelines provided by Bone Diagnostics, Inc. (Fort Atkinson, WI). One operator performed all pQCT scans and one technician performed all scan analyses. Repeat scanning of girls to establish the precision of pQCT was not considered ethical by the University of Arizona Human Subjects Protection Committee. Thus, we conducted a separate study with adults to determine within-subject ($n = 29$ per skeletal site) pQCT precision error (coefficient of variation: CV). After subject repositioning, CVs calculated as described by Glüer et al. [26] for trabecular vBMD at the 4% femur and tibia were 0.5% and 0.8%, respectively. CVs for femur and tibia periosteal circumference were 0.4% and 1.1%, respectively. CVs for BSI at the 4% femur and tibia were 0.9% and 0.8%, respectively, while CVs for SSI at the 20% femur and 66% tibia were 0.9% and 0.9%, respectively.

Total body mass, fat mass, percent total body fat, and lean soft tissue mass were obtained from DXA whole body scans using GE Lunar Prodigy (software version 5.60.003) fan-beam densitometer (GE Lunar Corp, Madison, WI, USA). Subjects were positioned using standard GE/Lunar protocols. DXA CVs and BMD precision in our laboratory have been previously reported [27].

Statistical Analysis

Data were checked for outliers and normality using histograms and all variables were tested for skewness and kurtosis. BSI and SSI at all sites were modestly skewed. We ran both log transformed and untransformed analyses; all results were similar, thus, we report the untransformed data for clarity. Quintiles of PYPAQ score divided the sample into five groups (fifths) and descriptive statistics were calculated for the total sample and for each fifth. Differences in descriptive statistics among fifths of PYPAQ score were analyzed using ANOVA and χ^2 tests as appropriate. We chose quintiles as group cut-offs to compare bone parameters across levels of PYPAQ score (i.e., fifths) for reasonable spread across groups,

while also preserving adequate group sample size to detect significant between-group differences. Bivariate correlations were computed using Pearson's r to identify relationships among PA variables (duration, frequency, load, PYPAQ score) and between PA variables and bone parameters. Significant independent relationships of bone parameters with PA duration, frequency, load, PYPAQ score, maturity offset, body mass, leg length, and ethnicity were assessed using stepwise multiple linear regression. The percentage of variation (R^2) in each bone parameter explained by PA duration, frequency, load, and PYPAQ score, together with all covariates, was calculated using the stepwise linear regression model. The criterion for entry into the model was $p \leq 0.05$, and the criterion for removal from the model was $p \geq 0.10$. Prior to regression analyses, all variables were checked for normality, linearity, and homoscedasticity using residual plots. Colinearity among covariates was tested in each regression model and was not observed in any of the final models. Differences in bone parameters (adjusted for maturity offset, body mass, leg length, and ethnicity) among fifths of each PA variable were tested using ANCOVA. Bone parameters were similar among the middle 3 fifths of PYPAQ score; thus, we collapsed these fifths into a single group and used ANCOVA, with the same covariates, to determine whether there were differences between the middle group (average of the middle 3 fifths) and the lowest and highest fifths of PYPAQ score. In Figure 1, outcome values were normalized to the middle group; thus, setting the middle group values to 1.0 and lower and higher values to <1.0 and >1.0 , respectively. Normalization of values was necessary due to the differences in units among pQCT outcome variables. Given that mechanical loads in the lower limb are proportional to body mass and leg length [28], these measures were included as covariates in all regression and ANCOVA models. Bonferroni *post hoc* tests were used to adjust for multiple comparisons. All regression and ANCOVA analyses were repeated substituting maturity offset [17] with Tanner stage [14]. All results were similar, thus, we only report analyses that included maturity offset based on its higher relation with all bone parameters in this sample [11]. All analyses were also performed within maturity offset and Tanner stage maturity categories (maturity offset < 0 years from PHV (PRE) and ≥ 0 years from PHV (POST); Tanner stage I (prepubertal), Tanner stage II–III (early pubertal), Tanner stage IV–V (late pubertal)). A significance level of $p = 0.05$ was used in all tests. All analyses were performed using The Statistical Package for the Social Sciences for Windows, Version 18.0 (SPSS, Chicago, IL, USA).

Results

Descriptive characteristics are shown in Table 1 for the total sample ($n = 465$) and for fifths of PYPAQ score. Sample ethnicity was 22% Hispanic and 78% non-Hispanic; sample race was 88% white, 7% Asian, 3% black or African American, 0.5% Native American or Alaska Native, 0.5% Native Hawaiian or other Pacific Islander, and 1% other. Tanner stage distributions for the total sample were 33% prepubertal (stage I, $n = 155$), 60% early pubertal (stages II–III, $n = 280$), and 7% late pubertal (stages IV–V, $n = 30$). Maturity offset values indicated that girls were on average 1.1 years from PHV, with a range from 3.2 years prior to PHV to 1.4 years post PHV. Based on U.S. National Center for Health Statistics/Center for Disease Control percentiles for body mass index (BMI, kg/m^2) [29], 3.0% of the sample was underweight (BMI < 5 th percentile), 73.8% of the sample was healthy weight (BMI 5th–85th percentile), 15.1% of the sample was at-risk for overweight (BMI 85th–95th percentile), and 8.1% of the sample was overweight (BMI > 95 th percentile).

As expected, PYPAQ score was significantly ($p < 0.001$) correlated with duration ($r = 0.63$), frequency ($r = 0.65$), and load ($r = 0.53$). Furthermore, PA duration, frequency, and load were significantly ($p < 0.001$) intercorrelated. Load was highly correlated with duration ($r = 0.71$) and frequency ($r = 0.69$), while duration and frequency were moderately correlated ($r = 0.48$). Bone parameters reflecting bone geometry (cortical area, EC, PC, cortical

thickness) and strength (BSI, SSI) at metaphyseal (4%) and diaphyseal (20% femur, 66% tibia) sites were significantly correlated with duration, load, and PYPAQ score ($r = 0.10$ – 0.20). Correlations between PYPAQ score and trabecular vBMD were also significant, although lower overall ($r = 0.10$ – 0.12). Frequency was not significantly correlated with any bone parameter at any site, except femur and tibia SSI. Also, PA components were not significantly correlated with cortical vBMD.

Stepwise multiple linear regression was used to determine independent associations of PA duration, frequency, load, and PYPAQ score with bone parameters when all PA variables were included together in regression models, with covariates, maturity offset, body mass, leg length, and ethnicity (Table 2). In this analysis, duration (minutes/session) was significantly and independently associated with 20% femur cortical area, PC, and SSI, 4% tibia BSI, and 66% tibia EC, PC, and SSI, while frequency (sessions/week) was significantly and independently associated with 20% femur cortical area and SSI and 4% tibia PC (Table 2). Load (peak strain score) was significantly and independently associated with 4% femur PC, 20% femur SSI, 4% tibia BSI, and 66% tibia PC (Table 2). PYPAQ score was significantly associated with all parameters reflecting bone geometry (cortical area, EC, PC) and strength (BSI, SSI), except diaphyseal cortical thickness and 4% femur PC, and explained 0.3–1.4% more variance in almost all bone parameters as compared to any individual PA component (Table 2). The single exception was that duration explained 5.9% of the variance in 66% tibia EC, while PYPAQ score explained 4.1% of the variance in the same parameter (Table 2). PA duration, frequency, and load also explained between 0.4% and 2.3% of the variance in some, but not all bone parameters reflecting bone geometry (cortical area, EC, PC) and strength (BSI, SSI) at various sites (Table 2). Duration, frequency, load, and PYPAQ score were not significantly associated with cortical or trabecular vBMD (data not shown).

Comparisons of bone parameters across fifths of PA duration, frequency, and load, as well as PYPAQ score, were performed using ANCOVA, adjusted for maturity offset, body mass, leg length, and ethnicity. Although there were some significant differences between the lowest and highest fifths of PA duration for some bone parameters, the differences were not consistent across skeletal sites. No significant differences in bone parameters were found across fifths of PA frequency and load. In contrast, differences in bone geometric parameters and indices of bone strength between the highest and lowest fifths of PYPAQ score were all significant, except for 4% femur BSI, diaphyseal cortical area, and diaphyseal cortical thickness (Table 3). A 2.7–3.8% greater PC and a 3.6–5.9% greater EC was observed in the highest as compared to the lowest fifth of PYPAQ score (Table 3). Also, the highest fifth of PYPAQ score had greater BSI (6.5–8.7%) and SSI (7.5–8.1%) as compared to the lowest fifth (Table 3). No significant differences in cortical or trabecular vBMD were observed among fifths of PA variables (Table 3). Analyses within maturity categories (maturity offset < 0 years from PHV (PRE) and ≥ 0 years from PHV (POST); Tanner stage I (prepubertal), Tanner stages II – III (early pubertal), Tanner stages IV – V (late pubertal)) gave similar results and did not change the magnitude or direction of the observed relationships between PA duration, frequency, load, and total PYPAQ score and bone parameters.

Bone parameters were similar among the middle 3 fifths of PYPAQ score (Table 3); thus, we collapsed these fifths into a single group and used ANCOVA (adjusted for maturity, body mass, leg length, and ethnicity) to determine whether there were differences between the average of the middle 3 fifths and the lowest and highest fifths of PYPAQ score (Figure 1). Because of differences in units among pQCT bone parameters, the results were normalized to the middle group, which was assigned a value of 1.0. Bone parameters for the highest fifth of PYPAQ score were not different from the average of the middle 3 fifths except for 66% tibia EC. In contrast, all bone parameters were significantly reduced in the lowest fifth as compared with the average of the middle 3 fifths of PYPAQ score, except for

4% femur BSI, diaphyseal cortical area, diaphyseal cortical thickness, and 66% tibia EC, showing that girls with low PYPAQ scores had smaller bone geometry (EC, PC) and less bone strength (BSI, SSI) compared to all other girls.

Discussion

Unlike past studies which have been constrained by the limitations of DXA, we examined whether any individual component of PA (duration, frequency, load), as well as a total PA score representing the interaction among all three PA components (duration $\times$ frequency $\times$ load), was associated with vBMD, geometry, and indices of bone strength in young girls using pQCT to measure bone parameters. PA duration, frequency, and load were all modestly and independently associated with bone geometry and strength, although duration was consistently the strongest predictor of bone parameters. As could be expected, the interaction of PA subcomponents (PYPAQ score) was the strongest predictor of bone parameters. Despite the heterogeneous cohort of pre- and peri-pubertal girls and inherent limitations in measuring PA in youth, PYPAQ score was a significant predictor of bone geometric parameters and indices of bone strength. These findings support the premise that mechanical loading during growth has the potential to optimize bone structure and produce worthwhile gains in bending, compressive, and torsional strength [10]. If maintained, these gains have the potential to reduce fracture risk later in life.

The influence of PA duration, frequency, and load on bone parameters has received little attention in youth [30–32]. Karlsson et al. [30] reported that weekly duration (hours/week) of exercise was associated with higher aBMD of adult male soccer players. Wang et al. [31] used DXA and pQCT and reported that participation in high-impact activities (greater loads) was associated with greater diaphyseal tibia parameters (cortical vBMD, total cross-sectional area, polar moment of inertia) of pre-, but not early-pubertal girls. More recently, Temaki et al. [32] reported in boys and girls that frequency of sports club participation, independent of activity load or duration, was predictive of aBMD. Our results extend previous findings because we studied the independent association between each of the three PA components and bone parameters using a 3-dimensional imaging method (pQCT) that is appropriate for growing children. Although we found independent associations between PA duration, frequency, load and bone geometry (cortical area, EC, PC) and indices of bone strength (BSI, SSI), these associations were modest and site specific. The association of activity duration (minutes/session) with bone parameters was greater than that of frequency (sessions/week) and load (peak strain score) at most skeletal sites. The potential importance of duration is consistent with studies of animals that have shown that prolonged loading sessions can continue to stimulate bone formation as long as the distribution of strain is altered throughout the session [7]. Human studies have emphasized PA load and frequency over duration. One reason PA duration has received less attention may be because this term can interpreted meaning either duration of the average training session (minutes/session) or the length of training history (years). While increasing the years of training history is known to be osteogenic [30, 33, 34], we found only one study that has addressed the question of whether increasing the duration of a typical training session is also osteogenic [35]. Another reason this question has received insufficient attention may be because studies in animals have shown that the osteogenic response to loading saturates relatively quickly [36, 37]. Based on these studies, prolonging the duration of a single training session is less likely to be osteogenic. However, animal studies have also shown that increased duration (e.g., increased number of loading cycles) can continue to stimulate bone formation as long as the distribution of strain is altered throughout the loading session [7], which is predominately the case during most activities in free-living humans. Thus, increasing the duration of the average training session may be an important osteogenic stimulus in humans that has been overlooked.

As expected, our findings showed that the interaction of PA duration, frequency, and load (total PYPAQ score) explained more variance in almost all bone parameters as compared to any individual PA component. Parameters reflecting bone geometry and indices of bone strength were 2.7–5.9% and 6.5–8.7% greater, respectively, in the highest compared to the lowest fifth of PYPAQ score. Nilsson et al. [38] have recently reported in young adult men (~19 years of age) that previous sport activity during childhood and adolescence was associated with increased PC of the tibial diaphysis compared with men who were inactive during growth. In agreement with Nilsson and colleagues [38], our findings showed that low active girls (lowest fifth of PYPAQ score) compared with more active girls (average of the middle 3 fifths and the highest fifth of PYPAQ score), had lower values on almost all bone parameters reflecting bone geometry (EC, PC) and bone strength (BSI, SSI) at metaphyseal and diaphyseal sites of the femur and tibia. Furthermore, the differences between girls with high PA versus moderate PA were attenuated compared to differences between girls with low versus moderate PA. These findings suggest that physical inactivity during growth may be detrimental for bone development.

Exercise before and during puberty has been associated with greater bone size (i.e., periosteal expansion) [38–42]. In a randomized controlled trial in prepubertal children, Specker and Binkley reported increased PC in response to 12 months of exercise [40] that persisted for 12 months post intervention [41]. However, further studies are needed to confirm these results because, as reported by the authors pQCT scan quality was poor on a large proportion (51%) of the baseline measurements [40]. Bass et al. [42] have suggested that exercise before and during the early pubertal years enhances periosteal apposition, whereas when undertaken late in puberty, exercise results in endocortical contraction. Thus, exercise during the pre- and/or early-pubertal years may be the most opportune time to modify bone strength, because periosteal expansion is a more effective means of increasing bone strength than endocortical contraction [9]. Our findings were similar in pre- and early-pubertal girls and showed that exercise was associated with periosteal and endosteal expansion during both periods, resulting in distribution of the cortex further from the center of the longitudinal axis of the bone. Hence, the greater bone strength observed in girls in the highest compared to the lowest fifth of PYPAQ score independent of differences in cortical area and thickness. Future prospective studies will be necessary to determine whether exercise during the late pubertal years continues to enhance periosteal and endosteal expansion or whether, after menarche, exercise works in concert with higher estrogen concentrations to promote endocortical contraction.

Only one study has previously examined the relation between PA and cortical bone size and vBMD in young girls [31]. Using pQCT, Wang et al. [31] reported that weight-bearing PA was associated with cortical bone size and vBMD of the diaphyseal tibia in pre-, but not in early-pubertal girls. Our results confirmed the finding that PA is related to tibial cortical bone size, but do not support a significant association with cortical vBMD at diaphyseal sites of the femur and tibia. One explanation for why we did not find a significant association between PA and cortical vBMD may be because most of the girls in our study were in an early pubertal ($n = 280$) stage of maturation. It is possible that the higher estrogen levels associated with puberty attenuated the relationship between PA and cortical vBMD. Our findings are consistent with other studies using pQCT in pre-pubertal gymnasts [43] and adult women [44], suggesting that mechanical loading is associated with cortical bone size, but not cortical vBMD. To date, the available data on the relationship between PA and trabecular vBMD at metaphyseal sites of weight-bearing bones are limited and conflicting [38, 39, 43, 44]. Although we found a significant correlation between PA and trabecular vBMD at the distal femur and tibia, the relationship was no longer significant after adjustment for covariates known to affect bone parameters (maturity, body mass, leg length, and ethnicity).

Our study is not without limitations. The main limitation is the difficulty in assessing PA in children and youth through a self-report questionnaire. We sought to minimize this limitation by using a questionnaire that has been validated in youth [19], by encouraging guardian assistance with PA recall, and by limiting recall to past year leisure-time PA and sport participation. Nevertheless, we acknowledge that this approach may be susceptible to reporting errors. Another potential limitation of the PYP AQ is that it does not allow for the examination of the relationship between historical PA (previous years) and bone parameters. For example, it is possible that older girls could have been physically active for more years. However, as recently shown by Nilsson et al. [45], present PA (past year) and historical PA (previous years) are strongly interrelated, which suggests that present PA tends to be representative of historical PA. Thus, had we measured historical PA in addition to present PA, like Nilsson et al. [45], it is probable we would have found both present and historical PA to be related to bone geometry and strength. Also, ground reaction forces (GRFs) associated with activities were not measured directly in our sample. Similar to Shedd et al. [20] and Wang et al. [31], we assigned load (peak strain score) values to activities based on GRFs reported in the literature for young females [22]. Another concern is that maturational differences may have influenced our study results. Although we did not directly assess skeletal age, we did control for maturation using Tanner staging [14] and maturity offset [17]. Both methods have limitations. Tanner stage estimates were obtained from a self-report questionnaire, a potential limitation, although the questionnaire has been shown to agree well with physician exam and grading of sexual maturation [15]. Maturity offset, defined as years from PHV, was estimated using the method of Mirwald et al. [17], who developed gender-specific algorithms to predict years from PHV. While PHV is best captured from longitudinal somatic measurements, the Mirwald equations [17] were developed from a large sample of youth [18] and have been shown to give reasonable estimates of maturity offset [16]. Both methods gave similar results, suggesting maturity was adequately controlled. Lastly, our cross-sectional analysis does not allow for determination of a causal relationship between PA and bone parameters. Future longitudinal trials are needed to address this proposition.

Despite these limitations, the study had several significant strengths, including the large sample of pre- and peri-pubertal girls and the use of pQCT, which has been used in only one previous study [31] with a similar focus. Furthermore, the inclusion of several sites at metaphyseal and diaphyseal regions of the femur and tibia provided a more detailed description of how PA duration, frequency, load, and PYP AQ score are related to vBMD, geometry, and indices of strength of weight-bearing bones. Our results indicate that a higher PYP AQ score during growth is predominantly associated with greater periosteal expansion. Since small changes in the shape of bone (e.g. an increase in the outer circumference) can dramatically increase bone strength and fracture resistance [9], these findings support the premise that loading exercises during growth may modify bone structure and reduce the risk of fracture later in life.

In conclusion, using pQCT in a large sample of pre- and peri-pubertal girls, we showed that PA duration, frequency, and load are associated with bone geometry and indices of strength, although their independent influence was modest and site specific. Contrary to our hypothesis based on findings from animal studies [4–6], PA duration (defined as average minutes/session) was a stronger predictor of bone parameters than PA frequency (sessions/week) and load (peak strain score [22]) at most skeletal sites, although the total PYP AQ score, which accounts for duration, frequency, and load, was a stronger predictor of bone geometry and strength than any individual component of PA. Girls with low levels of bone-relevant activity clearly had less favorable bone geometric parameters and lower indices of bone strength than girls with moderate levels; the differences between girls with high versus moderate PA were attenuated compared to differences between girls with low versus

moderate PA. These results highlight the importance of identifying girls with low levels of PA and encouraging them to engage in bone-building PA.

Acknowledgments

We appreciate the participation and support of principals, teachers, parents and students from the schools in the Catalina Foothills and Marana School Districts. We also wish to thank the radiation technicians, program coordinators, and all other members of the Jump-In Study team for their contribution. The project described was supported by Award Number HD-050775 (SG) from the National Institute of Child Health and Human Development. JF was supported by NIH NIGMS T32 GM-08400: Graduate Training in Systems and Interactive Physiology. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute of Child Health and Human Development or the National Institutes of Health.

Grant Support: NIH: HD050775

REFERENCES

1. Cooper C. Epidemiology of osteoporosis. *Osteoporos Int.* 1999; 9(Suppl 2):S2–8. [PubMed: 10525719]
2. Heaney RP, Abrams S, Dawson-Hughes B, et al. Peak bone mass. *Osteoporos Int.* 2000; 11:985–1009. [PubMed: 11256898]
3. Hopper JL, Green RM, Nowson CA, et al. Genetic, common environment, and individual specific components of variance for bone mineral density in 10- to 26-year-old females: a twin study. *Am J Epidemiol.* 1998; 147:17–29. [PubMed: 9440394]
4. Rubin CT, Lanyon LE. Regulation of bone mass by mechanical strain magnitude. *Calcif Tissue Int.* 1985; 37:411–417. [PubMed: 3930039]
5. Turner CH, Forwood MR, Rho JY, Yoshikawa T. Mechanical loading thresholds for lamellar and woven bone formation. *J Bone Miner Res.* 1994; 9:87–97. [PubMed: 8154314]
6. Hsieh YF, Turner CH. Effects of loading frequency on mechanically induced bone formation. *J Bone Miner Res.* 2001; 16:918–924. [PubMed: 11341337]
7. Lanyon LE. Functional strain in bone tissue as an objective, and controlling stimulus for adaptive bone remodelling. *J Biomech.* 1987; 20:1083–1093. [PubMed: 3323200]
8. Farr JN, Lee VR, Blew RM, Lohman TG, Going SB. Quantifying bone-relevant activity and its relation to bone strength in girls. *Med Sci Sports Exerc.* 2010 In Press.
9. Seeman E, Delmas PD. Bone quality—the material and structural basis of bone strength and fragility. *N Engl J Med.* 2006; 354:2250–2261. [PubMed: 16723616]
10. Seeman E. Invited Review: Pathogenesis of osteoporosis. *J Appl Physiol.* 2003; 95:2142–2151. [PubMed: 14555675]
11. Farr JN, Chen Z, Lisse JR, Lohman TG, Going SB. Relationship of total body fat mass to weight-bearing bone volumetric density, geometry, and strength in young girls. *Bone.* 2010; 46:977–984. [PubMed: 20060079]
12. American Academy of Pediatrics. Medical conditions affecting sports participation. *Pediatrics.* 2001; 107:1205–1209. [PubMed: 11331710]
13. Lohman, TG.; Roche, AF.; Martorell, R. Anthropometric Standardization Reference Manual. Human Kinetics; Champaign, IL: 1988.
14. Tanner, JM. Foetus into Man: Physical Growth from Conception to Maturity. Harvard Press; Cambridge, MA, USA: 1978.
15. Morris NM, Udry RJ. Validation of a Self-Administered Instrument to Assess Stage of Adolescent Development. *J Youth Adolesc.* 1980; 9:271–280.
16. Sherar LB, Baxter-Jones AD, Mirwald RL. Limitations to the use of secondary sex characteristics for gender comparisons. *Ann Hum Biol.* 2004; 31:586–593. [PubMed: 15739387]
17. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc.* 2002; 34:689–694. [PubMed: 11932580]
18. 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; 14:1672–1679. [PubMed: 10491214]
19. Aaron DJ, Kriska AM, Dearwater SR, Cauley JA, Metz KF, LaPorte RE. Reproducibility and validity of an epidemiologic questionnaire to assess past year physical activity in adolescents. *Am J Epidemiol.* 1995; 142:191–201. [PubMed: 7598119]
 20. Shedd KM, Hanson KB, Alekel DL, Schiferl DJ, Hanson LN, Van Loan MD. Quantifying leisure physical activity and its relation to bone density and strength. *Med Sci Sports Exerc.* 2007; 39:2189–2198. [PubMed: 18046190]
 21. Ridley K, Ainsworth BE, Olds TS. Development of a compendium of energy expenditures for youth. *Int J Behav Nutr Phys Act.* 2008; 5:45. [PubMed: 18782458]
 22. Groothausen J, Siemer H, Kemper G, Twisk J, Welten D. Influence of peak strain on lumbar bone mineral density: an analysis of 15-year physical activity in young males and females. *Pediatr Exerc Sci.* 1997; 9:159–173.
 23. Stratec Medizintechnik 2004 XCT 3000 manual, software version 5.40. Pforzheim, Germany:
 24. Kontulainen SA, Johnston JD, Liu D, Leung C, Oxland TR, McKay HA. Strength indices from pQCT imaging predict up to 85% of variance in bone failure properties at tibial epiphysis and diaphysis. *J Musculoskelet Neuronal Interact.* 2008; 8:401–409. [PubMed: 19147978]
 25. Lee DC, Gilsanz V, Wren TA. Limitations of peripheral quantitative computed tomography metaphyseal bone density measurements. *J Clin Endocrinol Metab.* 2007; 92:4248–4253. [PubMed: 17684050]
 26. Gluer CC, Blake G, Lu Y, Blunt BA, Jergas M, Genant HK. Accurate assessment of precision errors: how to measure the reproducibility of bone densitometry techniques. *Osteoporos Int.* 1995; 5:262–270. [PubMed: 7492865]
 27. Going S, Lohman T, Houtkooper L, et al. Effects of exercise on bone mineral density in calcium-replete postmenopausal women with and without hormone replacement therapy. *Osteoporos Int.* 2003; 14:637–643. [PubMed: 12844212]
 28. Ruff CB. Body size, body shape, and long bone strength in modern humans. *J Hum Evol.* 2000; 38:269–290. [PubMed: 10656779]
 29. Kuczmarski RJ, Ogden CL, Grummer-Strawn LM, et al. CDC growth charts: United States. *Adv Data.* 2000; 8:1–27. [PubMed: 11183293]
 30. Karlsson MK, Magnusson H, Karlsson C, Seeman E. The duration of exercise as a regulator of bone mass. *Bone.* 2001; 28:128–132. [PubMed: 11165954]
 31. 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; 15:100–106. [PubMed: 15773864]
 32. Tamaki J, Ikeda Y, Morita A, Sato Y, Naka H, Iki M. Which element of physical activity is more important for determining bone growth in Japanese children and adolescents: the degree of impact, the period, the frequency, or the daily duration of physical activity? *J Bone Miner Metab.* 2008; 26:366–372. [PubMed: 18600403]
 33. 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.* 2002; 17:2281–2289. [PubMed: 12469923]
 34. Kannus P, Haapasalo H, Sankelo M, et al. Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. *Ann Intern Med.* 1995; 123:27–31. [PubMed: 7762910]
 35. Sardinha LB, Baptista F, Ekelund U. Objectively measured physical activity and bone strength in 9-year-old boys and girls. *Pediatrics.* 2008; 122:e728–736. [PubMed: 18762509]
 36. Rubin CT, Lanyon LE. Regulation of bone formation by applied dynamic loads. *J Bone Joint Surg Am.* 1984; 66:397–402. [PubMed: 6699056]
 37. Umemura Y, Ishiko T, Yamauchi T, Kurono M, Mashiko S. Five jumps per day increase bone mass and breaking force in rats. *J Bone Miner Res.* 1997; 12:1480–1485. [PubMed: 9286765]

38. Nilsson M, Ohlsson C, Mellstrom D, Lorentzon M. Previous sport activity during childhood and adolescence is associated with increased cortical bone size in young adult men. *J Bone Miner Res.* 2009; 24:125–133. [PubMed: 18767931]
39. Lorentzon M, Mellstrom D, Ohlsson C. Association of amount of physical activity with cortical bone size and trabecular volumetric BMD in young adult men: the GOOD study. *J Bone Miner Res.* 2005; 20:1936–1943. [PubMed: 16234966]
40. Specker B, Binkley T. Randomized trial of physical activity and calcium supplementation on bone mineral content in 3- to 5-year-old children. *J Bone Miner Res.* 2003; 18:885–892. [PubMed: 12733728]
41. Specker B, Binkley T, Fahrenwald N. Increased periosteal circumference remains present 12 months after an exercise intervention in preschool children. *Bone.* 2004; 35:1383–1388. [PubMed: 15589220]
42. 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; 17:2274–2280. [PubMed: 12469922]
43. Ward KA, Roberts SA, Adams JE, Mughal MZ. Bone geometry and density in the skeleton of pre-pubertal gymnasts and school children. *Bone.* 2005; 36:1012–1018. [PubMed: 15876561]
44. Uusi-Rasi K, Sievanen H, Pasanen M, Oja P, Vuori I. Associations of calcium intake and physical activity with bone density and size in premenopausal and postmenopausal women: a peripheral quantitative computed tomography study. *J Bone Miner Res.* 2002; 17:544–552. [PubMed: 11874246]
45. Nilsson M, Ohlsson C, Sundh D, Mellstrom D, Lorentzon M. Association of physical activity with trabecular microstructure and cortical bone at distal tibia and radius in young adult men. *J Clin Endocrinol Metab.* 2010:2009–2258. doi:10.1210/jc.

Specific Remarks

More efficacious physical activity (PA) prescriptions for optimal bone development are needed. This study showed that PA duration, frequency, and load were all independently associated with bone parameters in young girls. Increased PA duration, frequency, and load are all important osteogenic stimuli that should be incorporated into future PA interventions.

Fig. 1.

Femur (a) and tibia (b) pQCT estimated marginal means $\pm$ SE for the lowest, average of the middle 3, and the highest fifths of past year physical activity questionnaire (PYPAQ) score normalized to the middle 3 fifths. Outcome values were normalized to the middle group; thus, setting the middle group values to 1.0 and lower and higher values to <1.0 and >1.0 , respectively. Normalization of values was necessary due to the differences in units among pQCT outcome variables. Differences in outcome values were evaluated by ANCOVA using maturity offset, body mass, leg length, and ethnicity as covariates. PC = periosteal circumference (mm); BSI = bone strength index (mg^2/cm^4); EC = endosteal circumference (mm); SSI = strength-strain index (mm^3). ^a $p < 0.05$ (lowest vs. middle); ^b $p < 0.01$ (lowest vs. middle); ^c $p < 0.05$ (lowest vs. highest); ^d $p < 0.01$ (lowest vs. highest); ^e $p < 0.001$ (lowest vs. highest); ^f $p < 0.05$ (middle vs. highest).

Table 1
Descriptive characteristics of all girls and by fifths of past year physical activity questionnaire (PYPAQ) score

	Total sample (n = 465)	Fifths of past year physical activity questionnaire (PYPAQ) score				
		First (n = 93)	Second (n = 93)	Third (n = 93)	Fourth (n = 93)	Fifth (n = 93)
PYPAQ score [*]	859.4 ± 913.0	192.8 ± 77.8 ^{b,c,d}	401.8 ± 51.6 ^{f,g}	618.9 ± 79.7 ^{b,h,i}	952.8 ± 119.7 ^{c,f,h,j}	2130.6 ± 1346.6 ^{d,g,i,j}
Duration [†]	411.7 ± 270.9	174.5 ± 94.9 ^{a,b,c,d}	289.0 ± 93.1 ^{a,e,f,g}	396.2 ± 173.1 ^{b,e,h,i}	525.7 ± 198.8 ^{c,f,h,j}	673.0 ± 270.9 ^{d,g,i,j}
Frequency [‡]	14.1 ± 10.1	5.9 ± 3.7 ^{a,b,c,d}	9.3 ± 4.1 ^{a,f,g}	12.0 ± 6.1 ^{b,h,i}	17.0 ± 7.5 ^{c,f,h,j}	26.3 ± 11.8 ^{d,g,i,j}
Load [§]	12.2 ± 6.8	6.0 ± 2.9 ^{a,b,c,d}	9.5 ± 3.5 ^{a,e,f,g}	11.9 ± 5.3 ^{b,e,h,i}	15.5 ± 5.9 ^{c,f,h,j}	18.2 ± 7.6 ^{d,g,i,j}
Ethnicity (%; Hispanic)	22	24	20	17	30	19
Age (years)	10.6 ± 1.1	10.5 ± 1.1	10.4 ± 1.0 ^f	10.7 ± 1.0	10.9 ± 1.1 ^f	10.8 ± 1.1
Tanner stage (%; 1/2/3/4/5)	33/33/27/5/2	29/43/22/6/0	43/28/24/4/1	30/34/27/7/2	28/29/36/5/2	37/31/28/2/2
Maturity offset (years)	-1.1 ± 1.0	-1.2 ± 1.1	-1.4 ± 0.9 ^f	-1.1 ± 1.1	-0.9 ± 1.0 ^f	-1.1 ± 1.0
Body mass (kg)	39.2 ± 10.4	40.9 ± 12.4	37.1 ± 9.2	37.5 ± 9.2	41.2 ± 10.5	39.3 ± 9.8
Height (cm)	144.3 ± 9.8	143.8 ± 9.4	142.3 ± 9.0 ^f	145.0 ± 10.2	146.5 ± 10.1 ^f	144.0 ± 9.8
BMI (kg/m ²)	18.6 ± 3.4	19.5 ± 4.1 ^{a,b}	18.1 ± 2.9 ^a	17.6 ± 2.7 ^{b,h}	19.0 ± 3.4 ^h	18.7 ± 3.2
Leg length (cm)	68.8 ± 5.7	68.5 ± 5.3	67.9 ± 5.4	69.4 ± 5.6	70.0 ± 6.4	68.3 ± 5.6
Femur length (cm)	34.0 ± 3.0	33.8 ± 2.8	33.4 ± 2.8 ^f	34.0 ± 2.9	34.9 ± 3.4 ^f	33.8 ± 3.0
Tibia length (cm)	33.2 ± 2.8	33.2 ± 2.8	32.8 ± 2.6	33.3 ± 2.9	33.8 ± 2.7	32.8 ± 2.9
Body fat (%)	27.8 ± 8.4	31.2 ± 9.0 ^{a,b,d}	27.5 ± 7.6 ^a	25.1 ± 7.6 ^b	28.1 ± 8.3	27.2 ± 8.4 ^d

Values are presented as mean ± SD or percentage

^{*} PYPAQ score = $\sum_{n=1}^5$ (Duration (minutes/session) × Frequency ([months/12] × (days/week)) × Load (peak strain score))

[†] Duration = $\sum_{n=1}^5$ (minutes/session)

[‡] Frequency = $\sum_{n=1}^5$ ([months/12] × (days/week))

[§] Load = $\sum_{n=1}^5$ (peak strain score)

Significant ($p \leq 0.05$) difference between fifths:

^a first vs. second

- b* first vs. third
- c* first vs. fourth
- d* first vs. fifth
- e* second vs. third
- f* second vs. fourth
- g* second vs. fifth
- h* third vs. fourth
- i* third vs. fifth
- j* fourth vs. fifth, ANOVA

Table 2

Significant associations between duration, frequency, load, past year physical activity questionnaire (PYPAQ) score and pQCT bone parameters in young girls (n = 465)

	Duration [†]			Frequency [‡]			Load [§]			PYPAQ score [*]		
	β	p	R ² (%)	β	p	R ² (%)	β	p	R ² (%)	β	p	R ² (%)
<i>pQCT Femur</i>												
4% PC	-	-	-	-	-	-	0.06	0.030	0.6%	-	-	-
4% BSI	-	-	-	-	-	-	-	-	-	0.08	0.028	1.4%
20% Crt Area	0.05	0.047	0.4%	0.05	0.032	0.4%	-	-	-	0.07	0.003	0.7%
20% EC	-	-	-	-	-	-	-	-	-	0.07	0.050	1.0%
20% PC	0.05	0.047	0.4%	-	-	-	-	-	-	0.08	0.004	0.7%
20% Crt Thk	-	-	-	-	-	-	-	-	-	-	-	-
20% SSI	0.06	0.006	0.5%	0.06	0.013	0.4%	0.05	0.033	0.4%	0.08	<0.001	0.8%
<i>pQCT Tibia</i>												
4% PC	-	-	-	0.05	0.048	0.5%	-	-	-	0.07	0.012	0.8%
4% BSI	0.11	0.002	2.3%	-	-	-	0.09	0.006	1.9%	0.13	<0.001	3.3%
66% Crt Area	-	-	-	-	-	-	-	-	-	0.08	0.002	0.9%
66% EC	0.14	<0.001	5.9%	-	-	-	-	-	-	0.12	0.003	4.1%
66% PC	0.11	<0.001	1.8%	-	-	-	0.06	0.047	0.5%	0.12	<0.001	2.1%
66% Crt Thk	-	-	-	-	-	-	-	-	-	-	-	-
66% SSI	0.06	0.010	0.5%	-	-	-	-	-	-	0.11	<0.001	1.5%

Standardized regression coefficients (β), p values, and variances (R^2) in bone parameters explained by significant ($p < 0.05$) physical activity components from stepwise multiple linear regression models.

Variances (R^2) shown are for each separate physical activity component when all physical activity components (duration, frequency, load, and PYPAQ score) and covariates (maturity offset, body mass, leg length, and ethnicity) were included in regression models

PC = periosteal circumference (mm); BSI = bone strength index (mg^2/cm^4); Crt Area = cortical area (mm^2); EC = endosteal circumference (mm); Crt Thk = cortical thickness (mm); SSI = strength-strain index (mm^3)

* PYPAQ score = $\sum_{n=1}^N (\text{Duration (minutes/session)} \times \text{Frequency (months/12)} \times (\text{days/week})) \times \text{Load (peak strain score)}$

[†] Duration = $\sum_{n=1}^N (\text{minutes/session})$

[‡] Frequency = $\sum_{n=1}^N ((\text{months/12}) \times (\text{days/week}))$

[§] Load = $\sum_{n=1}^N (\text{peak strain score})$

non-significant contribution to the regression model ($p > 0.05$)

Table 3

pQCT bone parameters of girls by fifths of past year physical activity questionnaire (PYPAQ) score

	Fifths of past year physical activity questionnaire (PYPAQ) score *				
	First (n = 93)	Second (n = 93)	Third (n = 93)	Fourth (n = 93)	Fifth (n = 93)
<i>pQCT Femur</i>					
4% Trab vBMD	234.5 ± 3.2	235.4 ± 3.2	235.6 ± 3.2	239.6 ± 3.2	239.4 ± 3.2
4% PC	122.7 ± 0.8 ^d	125.5 ± 0.8	124.9 ± 0.8	125.7 ± 0.8	126.1 ± 0.8 ^d
4% BSI	91.5 ± 2.2	94.7 ± 2.2	95.6 ± 2.2	98.7 ± 2.2	97.6 ± 2.2
20% Crt vBMD	1043.8 ± 2.3	1046.8 ± 2.3	1051.7 ± 2.3	1045.8 ± 2.3	1042.9 ± 2.3
20% Crt Area	171.1 ± 1.8	177.1 ± 1.8	174.0 ± 1.8	176.5 ± 1.8	176.7 ± 1.8
20% EC	60.4 ± 0.6 ^d	61.7 ± 0.6	62.0 ± 0.6	62.5 ± 0.6	62.6 ± 0.6 ^d
20% PC	75.8 ± 0.5 ^{c,d}	77.5 ± 0.5	77.7 ± 0.5	77.8 ± 0.5 ^c	78.3 ± 0.5 ^d
20% Crt Thk	2.5 ± 0.03	2.6 ± 0.03	2.5 ± 0.03	2.5 ± 0.03	2.5 ± 0.03
20% SSI	1265.9 ± 19.4 ^{a,b,c,d}	1345.6 ± 19.4 ^a	1350.3 ± 19.4 ^b	1360.7 ± 19.4 ^c	1363.9 ± 19.4 ^d
<i>pQCT Tibia</i>					
4% Trab vBMD	219.6 ± 2.7	219.4 ± 2.7	222.7 ± 2.7	225.4 ± 2.7	226.2 ± 2.7
4% PC	84.6 ± 0.5 ^d	85.7 ± 0.5	86.0 ± 0.5	86.5 ± 0.5	87.0 ± 0.5 ^d
4% BSI	49.2 ± 1.0 ^{c,d}	51.0 ± 1.1	52.5 ± 1.1	53.5 ± 1.1 ^c	53.7 ± 1.1 ^d
66% Crt vBMD	1025.3 ± 2.9	1024.7 ± 2.9	1036.4 ± 2.9	1028.1 ± 2.9	1026.9 ± 2.9
66% Crt Area	185.1 ± 2.1 ^c	189.5 ± 2.1	189.8 ± 2.1	194.2 ± 2.1 ^c	190.7 ± 2.1
66% EC	51.0 ± 0.6 ^d	52.6 ± 0.6	51.9 ± 0.6	52.9 ± 0.6	54.1 ± 0.59 ^d
66% PC	70.3 ± 0.5 ^{c,d}	71.7 ± 0.5	71.7 ± 0.5	72.2 ± 0.5 ^c	73.0 ± 0.5 ^d
66% Crt Thk	3.0 ± 0.04	3.1 ± 0.04	3.1 ± 0.04	3.1 ± 0.04	3.0 ± 0.04
66% SSI	1115.9 ± 18.0 ^{c,d}	1163.6 ± 18.0	1186.8 ± 18.0	1199.8 ± 18.0 ^c	1209.5 ± 18.0 ^d

Values are presented as estimated marginal means ± SE adjusted for maturity offset, body mass, leg length, and ethnicity Trab vBMD = trabecular volumetric bone mineral density (mg/cm³); PC = periosteal circumference (mm); BSI = bone strength index (mg²/cm⁴); Crt vBMD = cortical volumetric bone mineral density (mg/cm³); Crt Area = cortical area (mm²); EC = endosteal circumference (mm); Crt Thk = cortical thickness (mm); SSI = strength-strain index (mm³)

Significant ($p < 0.05$) difference between fifths:

$$* \text{PYPAQ score} = \sum_{i=1}^n -1 \text{ (Duration (minutes/session) } \times \text{ Frequency (months/12) } \times \text{ Load (peak strain score))}$$

$a_{\text{first vs. second}}$

$b_{\text{first vs. third}}$

$c_{\text{first vs. fourth}}$

$d_{\text{first vs. fifth, ANCOVA}}$