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Interscholastic Athletics and Bone Strength: The Iowa Bone Development Study

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Abstract

The objective of this study was to determine the relationship between adolescents' participation in various interscholastic sports and differences in bone strength outcomes. Participants (N = 380) were recruited from the Iowa Bone Development Study and categorized based on sport participation into three power groups: no-, low- and high-power. The sports of basketball, cheerleading/poms, gymnastics, volleyball, track, football, tennis, and soccer were considered high-power. Peripheral quantitative computed tomography (pQCT) was used to determine bone measures of polar stress-strain index (measure of torsion strength), cortical content at the 66% tibia (measure of cortical bone size), and bone strength index (measure of compression strength based on total bone density and area at 4% tibia site). Adjusted pairwise comparison for group least squares means for high-power sport participation compared to no-power sport participation showed significant differences in all bone strength outcomes for both males and females (p-value < 0.01). There was a significant difference in all bone strength measures between low- and no-power groups for males (p-value < 0.05), but not females. Because of decreasing levels of physical activity (PA) in late adolescence, the promotion of high-power sports may be particularly important for optimal bone development in the final years prior to peak bone mass.

Keywords

bone strength; power sports; impact sports; pQCT; physical activity; exercise

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INTRODUCTION

More than 54 million Americans have osteoporosis, with approximately 50% of Caucasian women predicted to suffer from an osteoporosis related fracture during their lifetime resulting in a projected Medicare costs of $25.3 billion by 2025 (4). It is estimated that 60% of osteoporosis development risk can be explained by the amount of bone mass accumulated during the adolescent and early adult years, and that this accumulation can have greater positive effects than any interventions after the development of osteoporosis in adult life (3). Physical activity (PA) is commonly recommended for children and adolescents to promote strong and healthy bones since osteoblasts initiate bone formation as a result of weight bearing forces during PA, and have been shown to cover the bone surfaces at a greater proportion during childhood and adolescence (11). More specifically, moderate-and-vigorous intensity physical activity (MVPA) has been shown to stimulate greater bone mass and better geometry compared to lower activity levels (15). Since bone formation takes place at the greatest rate during childhood and adolescence, it has been suggested that it is most crucial that the necessary MVPA takes place during these critical years to reduce the chance of developing osteoporosis in adult life (11).

Bone health is particularly important for females because of the greater risk of osteoporosis in post-menopausal women (4). Furthermore, the number of adolescent females worldwide achieving the daily-recommended levels of MVPA is less than 20% and by late adolescence most females are sedentary (2,15). A recent study found that PA peaked at age 6 in both males and females and that PA levels decreased sharply until age 19 where it was similar to activity levels of 60 year olds (32). This exposes a high-risk period in childhood and adolescence for physical inactivity and potential for the development of osteoporosis in later life. One way to encourage increased levels of MVPA is through interscholastic sports. Previous research has demonstrated interventions that include both school and family or community involvement are the most effective at increasing levels of PA (31).

It has been well documented that jumping activities, long and more frequent activities with higher load durations, impact-loading PA, odd-impact loading PA and vigorous PA are all effective in bone remodeling for strength (6,19,22,26,36). This may be due to the strain placed on the bone by muscle forces and impact involved in these types of activities, which is explained in the Mechanostat Theory proposed by Frost and Schonau (7,8). This theory proposed that the greater the muscle force was on bone, the greater the bone adaptation would be.

Furthermore, researchers have found sports that sports using a ball typically have greater ground reaction forces (GRF) and involve jumping, cutting and sprinting with high-impact, multidirectional forces that help influence bone strength geometrically while promoting bone mass accrual (6,19,22,26,36). Basketball, volleyball, soccer and track athletes have been shown to have greater bone strength when compared to swimming athletes and controls (30). Basketball athletes also have greater bone strength than runners, and both volleyball and basketball players have greater bone strength than those that do not participate in any PA (1,20,23,24). While ball sports may demonstrate more beneficial effects than running, running still seems to produce better bone strength results in runners compared to non-runners (11,20,28). Additionally, gymnastics and cheerleading may produce beneficial bone health benefits. The sport of gymnasts is the most widely studied sport in terms of bone health and studies have shown positive bone formation from participation in the sport including long-term effects in ex-gymnasts (5,18,34). To date, only one study has been conducted on the effects of cheerleading on bone strength outcomes, which showed a positive influence on bone health (25).

In addition to higher GRFs and high impact having a positive impact on bone health in many of these sports, muscle power, the force exerted on bones by muscles, has also been shown to be predictive of increased bone strength (15,37). Because of this, an opportunity to promote high power interscholastic sport participation exists in order to improve the bone health of adolescents as they approach adulthood. This is of particular interest due to the decreasing levels of PA across the lifespan and the impact that decreased PA can have on bone health. To assist with better understanding the impact of power sports, the objective of this study was to determine the relationship between adolescents’ participation in various interscholastic sports and differences in bone strength outcomes, using data from the ongoing Iowa Bone Development Study (IBDS)(14,15). The primary focus was to determine whether participation in power sports was associated with better bone strength measures. We hypothesized that participation in high-power sports would be associated with higher bone strength during adolescence.

METHODS

Experimental Approach to the Problem

Three hundred eighty subjects participated in this study. Subjects were classified into three different power groups for sport participation: no-power, low-power and high-power. Sports were categorized based on previous literature from our group (33). High-power sports (females n=77; males n=25) were defined as being a part of a high school team for basketball, cheerleading or poms, gymnastics or volleyball for at least two years to allow sufficient time for bone adaptation. Low-power sports (females n=38; males n=79) were defined as being a member of any of the high-power sports teams for 1 year or being a part of a track, football, tennis, or soccer team for at least three years total. No-power sports subjects (females n=89; males n=72) were those who were not a part of a high school team for high-power sports or low-power sports for a specified amount of time. The Physical Activity Questionnaire for Adolescents (PAQ-A) was utilized to measure physical activity levels.

Participants

Participants were from the Iowa Bone Development Study (IBDS; NIH Clinical Trial NCT03547128), which is a longitudinal study on bone health during childhood, adolescence and young adulthood (14). Participants in the IBDS are a subset of the Iowa Fluoride Study birth cohort (17); 1,882 families from eight Iowa hospital post-partum wards were recruited between 1993 and 1997. Initial recruitment and examination of the IBDS cohort was conducted between 1998 and 2002 when subjects were approximately 5 years of age. The IBDS used rolling admission to allow Fluoride Study members to participate in any followup examinations. Approximately 95% of the IBDS subjects were white and two-thirds of parents had college degrees. The current analysis focused on data collected when subjects were approximately 17 years of age. The University of Iowa Institutional Review Board approved the present study (#199112665). Parents of subjects provided written informed consent and minors provided assent in the initial data collection.

Procedures

Subjects completed a clinical examination that included anthropometry and peripheral quantitative computed tomography (pQCT) of the lower leg at age 17. Research staff trained in anthropometry measured the subjects' weight (kg), standing height (cm) and using standardized protocols, sitting height (cm) at multiple longitudinal assessments. Weight was measured using a Healthometer physicians scale (Continental, Bridgeview, IL) and height measures were taken using a Harpenden stadiometer (Holtain, Crymych, UK). Maturity offset (year from peak height velocity; PHV) prediction equations established by Mirwald and colleagues (21) were used to determine somatic maturity. These equations include age, sex, weight, height, sitting height, and leg length as predictors. PHV estimates were calculated for all subjects using age 11 and 13 examination data for females and age 13 and 15 data for males, when available. The clinical examination (between age 11 and age 15), that provided an estimate of PHV age that was closest to the actual clinical examination age was used as the best estimate. For small number of participants with only one PHV estimate, it was used as the best.

Tibial measures for a majority of the subjects were acquired using pQCT software version XCT 6.00 (XCT 2000, Stratec, Inc.; Pforzheim, Germany). However, the Stratec SCT 3000 was used to acquire measures for the 27 subjects who had a calf circumference greater than 15.5 inches, which was too large to fit in the SCT 2000 gantry. An IBDS calibration study found good agreement between the two models. In that study, in vivo measurements were obtained at sites corresponding to 4 and 66% lengths of the tibia for 17 healthy adults (12 female; aged 21–58 years) on both machines within 6 weeks of each other. In this IBDS calibration study, cross-sectional bone area and bone mineral density for total and trabecular bone were determined for the 4% site. For paired measurements, the mean percentage differences in total bone are and bone density obtained with the XCT 3000 were within 1.5% of the values obtained with the XCT 2000 machine. In addition to these measures, polar Strength-Strain Index (pSSI) was determined for cortical bone at the 66% site. The mean difference in pSSI values obtained with the SCT 3000 were less than 2.2% compared with results from the XCT 2000 machine (unpublished data).

In light of inadequate evidence supporting the use of dominant versus non-dominant limb for the bone and muscle measures, the left leg was scanned, unless there was a history of fracture (<1% of subjects). Prior to scanning, tibial length was measured from the center of the medial malleolus to the proximal tibial plateau with the participant resting the lateral side of one foot on the contralateral knee. This value was entered into the scanner to standardize the regions of interest as percentages of individual bone length. A coronal scout view was acquired at the distal end of the tibia and an anatomical reference line was placed to bisect the medial side of the distal growth plate. Moving in a proximal direction from the reference line, the scanner was programmed to acquire measures at 4% and 66% of the tibia length with a voxel size of 0.4 mm, tomographic slice thickness of 2.2 mm, and scan speed of 20 mm/s. All pQCT scans were acquired by one of the three International Society for Clinical Densitometry (ISCD) certified bone densitometry technologists.

Analyses of the metaphyseal cross-section at the 4% site found total bone using interactive contour search mode 3 with the threshold set just above soft tissue density of 169 mg/cm^3. This effectively separates lower density soft tissue voxels from the higher density periosteal bone border and generates a volumetric total bone density outcome. Total bone compressional strength, or Bone Strength Index (BSI), (mg^2/mm^4), was calculated with the following formula: BSI (mg^2/mm^4) = Total Area (mm^2) x (Total Density (mg/mm^3)^2).

Analyses of the diaphyseal 66% cross-section were used to find pSSI and CoA. For pSSI, cort mode 2 with a threshold of 480 mg/cm^3 was used, as this was the software default threshold for the SSI. SSI was derived from section modulus using bone density as a material property. Each voxel is weighted based on a normal bone density of 1200 mg/cm^3 and applied to the equation by dividing each voxel density by 1200 mg/cm^3. Bending strength results are reported in the X and Y plane, but are not used because they are dependent on the bone rotation. pSSI is not dependent on rotation and is the preferred result to report. CoA was measured using separation mode 2 and a threshold of 710 mg/cm^3 combined with analysis filtering.

Scans were carefully checked for possible movement artifacts and quality at the time of initial scan analysis by a trained technician. Then, complete review of all scans was performed by another technician to ensure quality data. All scans that were found to have unacceptable levels of movements at any site of interest or imprecise reference line placement were excluded (4% total scans for age 17 subjects). Precision analysis has been performed for the 4% radius site on a small sample of subjects in the same age group. Two technicians showed high inter-rater reliability with intra-class correlation coefficients (ICC) exceeding 0.98 for all measures tested (total and trabecular area; total and trabecular density) and high test-retest reliability, ICC exceeding 0.98 for one technician and 0.76 to 0.99 for the other. Manufacturer supplied hydroxyapatite phantoms for pQCT were scanned daily.

Additionally, the Physical Activity Questionnaire for Adolescents (PAQ-A), developed by Kowalski et al. (16), was used to estimate PA levels. This is a validated and self-administered 7-day recall instrument developed for high school students in grades 9 through 12 or approximately ages 14 to 19 years of age. Total PAQ-A score was calculated from this instrument. Participants were also asked to report amount and type of high school interscholastic sport participation. This information was used to categorize power sport participation based on GRF and peak strain scores associated with different sports (10) and investigator knowledge of sport mechanics. Three different power groups for sport participation were established: no-power, low-power and high-power. High-power sports were defined as being a part of a high school team for basketball, cheerleading or poms, gymnastics or volleyball for at least two years to allow sufficient time for bone adaptation, since previous bone intervention studies indicate that a minimum of seven months is needed for bone adaptation (35). Two years of time would allow for two seasons of participation in the sport. Low-power sports were defined as being a member of any of the high-power sports teams for 1 year or part of a track, football, tennis, or soccer team for at least three years total. No-power sports subjects were not part of a high school team for high-power sports or low-power sports for a specified amount of time.

Statistical Analyses

All analyses were stratified by sex. Means and standard deviations were calculated to describe continuous characteristics of subjects. Normal probability plots showed no severe departure from normality for variables included in analyses. Student's t-test was used to compare male and female characteristics. Pearson correlation analysis was performed to investigate bi-variable associations between bone strength outcomes and potential covariates. Association between bone strength outcomes and high school varsity sport participation (three power sports groups) was investigated using sex-specific general linear models (analysis of covariance) with subjects' height, weight, and years from PHV included as important continuous covariates. Analyses of covariance was repeated including PAQ score at the time of bone scans as an additional covariate. Least squares means for bone strength measures across high school activity groups, adjusting for covariates, were calculated from analysis of covariance models and pairwise comparisons were performed (t-tests). SAS statistical software (version 9.4, SAS Institute, Inc., Cary, NC) was utilized for analyses and a p-value of < 0.05 was considered statistically significant.

RESULTS

The 380 subjects are described in Table 1. Males were significantly taller and heavier than females. They also had greater compressional bone strength, torsional bone strength and cortical content when compared to females. On average years from PHV for females was 5.7 years for females and 3.9 years for males ($p < 0.05$).

Pearson correlation analysis (data not shown) between bone strength outcomes and height, weight, maturity (years from PHV), and PAQ score confirmed that these variables needed to be adjusted for while investigating associations of bone strength with power sport participation. Least squares means for power sports participation groups estimated from analysis of covariance models and test results for pairwise groups comparisons are reported in Table 2 (adjusted for height, weight, and maturity) and 3 (additionally adjusted for PAQ score). Overall, group variable is statistically significant for all bone measures (overall F-statistic test p-value < 0.01).

Pairwise comparison for group least squares means for group 3 (high-power sports) compared to group 1 (no-power sports) showed significant differences in all bone strength outcomes for both males and females (p-value < 0.01). Group 2 (lower power sports) had estimated bone strength measure values between those that were obtained for group 1 (no-power sports) and group 3 (high-power sports). For example, the differences between group 2 and group 1 were statistically significant or borderline statistically significant for males for all bone strength measures (p-value $< 0.1/3$; Bonferroni correction for multiple comparisons). The differences between group 2 and group 1 were not statistically significant for females (p-value > 0.05/3). Additional adjustment for PAQ score did not change the patterns for estimated group means; the results were comparable.

DISCUSSION

The main purpose of this study was to determine the relationship between adolescents' participation in power sports and bone strength outcomes. A positive association was seen in both males and females between power sport participation in all bone outcomes (Figures 1–3). The findings also showed significant differences in bone strength measures between participation in sports that require different levels of power. This was true for both males and females in all bone strength outcomes including BSI, pSSI and cortical content. The greatest difference was between bone strength outcomes when comparing no-power to high-power subjects. The comparison between no-power and low-power resulted in significant differences in males, but no significant differences in females. There were only significant differences in cortical content of males and pSSI of females when comparing high-power to lower power subjects.

These results indicate that high-power sports are associated with high bone strength outcomes in late adolescence. Results also suggest that there are still benefits of participation in low-power sports as compared to no-power sport participation. Because of this, participation in high-power sports should be promoted to adolescents in order to achieve the greatest bone strength for future osteoporosis prevention. This same concept has been explained by the bone modeling threshold (8). A certain strain magnitude (via muscle forces and impact) must be reached in order for bone to achieve an osteogenic response and begin bone adaptation. Once the threshold is reached, osteocytes in the bones signal molecules to activate osteoblasts and osteoclasts to stimulate the adaptation (7). The concepts of the bone modeling threshold and the Mechanostat Theory could explain why the high-power group had much greater bone outcomes (7). Based on the results of our study, it could be hypothesized that the threshold may lie somewhere between the low-power sports and high-power sports. Once it was obtained, significant benefits on bone strength measures were seen in the subjects. This also consistent with the Mechanostat Theory because high-power sports require greater forces activation of muscles acting on the bones, which further contribute to bone remodeling (8).

The threshold effect was also observed by Sayers and colleagues (26). The relationship of PA to cortical bone mass in 1,748 males and females (mean age 15.5 years) using pQCT at the 50% tibia was measured. Accelerometers worn at the hip were used to measure PA over seven consecutive days to classify subjects in PA groups according to intensity (sedentary, light, moderate, and vigorous). In minimally adjusted analyses of cortical content and PA, there was little association with light PA on cortical content, some association with moderate PA and stronger evidence of association with vigorous PA. When the analyses were adjusted for total PA, an evidence of a relationship of cortical content with moderate PA was not detected. This suggested a threshold effect where only vigorous PA had a significant effect on cortical content. The same results were obtained when analyses were adjusted for pubertal stage and for SSI. Accelerometers signals measured at the hip would be created by high lower body muscle loads and therefore be parallel to high-power activity that we used as our exposure variable in the present study.

Other studies examining organized sport activity also saw positive associations between participation and bone strength. Greene and colleagues (9) studied twenty 16-year-old (SD = 1.7 years) female mid-distance runners and compared them to twenty age-matched controls to examine BSI. The runners had an average of 2.1 hours of physical activity per week, while the controls had an average of 0.07 hours per week. Bone mineral content, BSI, cortical bone volume, volumetric cortical BMD and cross-sectional moments of inertia were higher in the distal tibia of athletes than controls. These findings echoed the increased BSI in athletes exposed to higher training loads as compared to non-active controls and gave evidence of PA having a positive effect on the bones of females in late adolescence.

Additionally, results of previous IBDS reports showed that children who participated in high levels of PA had significantly greater bone strength, but also highlighted a decrease in PA levels in adolescence. For example, the group of once highly active females fell to a low level of activity by the time they reached the age of 17 and had an activity level similar to that of their inactive peers. An additional IBDS report showed that bone strength could be predicted by measuring muscle power through the use of a simple vertical jump test (15). Although muscle power has been shown to be a good predictor of bone strength, it is a newer concept. Because existing literature focuses on impact, not power, to assess bone strength, our current study applied the concept of power via sorting interscholastic athletes into three groups based on presumed power loads that would occur during participation. We then looked for differences in bone strength outcomes among these groups. Uniquely our analysis used pQCT to measure bone strength. pQCT is a three dimensional technique using low radiation doses that quantifies volumetric bone mineral density (29). While the majority of reviewed studies have used dual-energy x-ray absorptiometry (DXA), two-dimensional tool for assessing bone mineral density, pQCT may serve as a better predictor for overall bone strength measures such as bone density and bone geometry (27).

The findings of the current study are promising because it demonstrates that 17-year-old adolescents may be maintaining or perhaps even increasing bone strength through high-power sports. Sports participation should be promoted in high school, especially since most school-related sports present lower barriers to access, making it easier for adolescents to participate. Gunter and colleagues (11) also stated that to date, the most effective interventions for skeletal development enhancement have been school-based. For example, Gunter and colleagues (12) studied the effects of a 7-month jumping intervention in pre-pubertal boys and girls. Immediately following the intervention, BMC values were significantly greater than controls for lumbar spine (LS), total hip (TH), femoral neck (FN) and whole body (WB). Three years after the intervention, the intervention group still had greater BMC than controls at 2.3%, 3.2% 4.4% and 2.9% at LS, TH, FN and WB, respectively. These results show the long-lasting effects high-power PA may have on bone outcomes.

Limitations of the current study include the cross-sectional nature of bone measures at age 17. One disadvantage of a cross-sectional study is the difficulty of making causal inferences from data because they only provide a snapshot of situational data. Additionally, study subjects were drawn from a regional sample of babies born in Iowa. Because of this, generalization of study results to other geographic areas, particularly with more ethnic and racial variability, should be performed with caution. Because questionnaires were used to measure activity, answers could have been slightly varied from reality due to social desirability.

It is also possible that the high-power sports group had greater bone strength due to genetics or dietary intake, particularly calcium and vitamin D, as these variables were outside the scope of the current study. Protein, the vitamins C, D and K, and the minerals copper, manganese, zinc and phosphorous all play a role in bone tissue deposition, maintenance and repair through cellular processes (13). Any deficiencies in these nutritional components could have played a role in bone strength results. Hereditary factors have also been found to exert powerful effects on peak bone mass (13). Finally, high-power activities are also by nature also high impact activities; the latter is also known to improve bone strength.

PRACTICAL APPLICATIONS

This study suggests a positive relationship between high-power sports and bone strength in late adolescence. On average individuals engaged in high-power sports had greater bone strength. These findings support the promotion of sports participation in interscholastic high-power sports. However our results also showed more benefits in participation of any kind of PA, low or high-power, over no participation in any PA. Because of decreasing levels of general PA in late adolescence, the promotion of these activities may be even more important for optimal bone development than previously appreciated.

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Table 1.

Subjects' Characteristics by Sex

Characteristics	Males (N=176) Mean (SD)	Females (N=204) Mean (SD)
Age at scan (years)	17.6 (0.4)	17.5 (0.4)
Maturity (years from PHV age)	3.9 (0.9) [**]	5.7 (0.7)
Height (cm)	79.9 (18.6) [**]	66.6 (16.2)
BSI, compression, 4% tibia site (mg^2/mm^4)	178.9 (7.8) [**]	165.8 (6.7)
pSSI, 66% tibia site (mm^3)	134.1 (31.5) [**]	98.5 (23.3)
Cortical content, 66% site (mg)	3047.0 (660.5) [**]	2215.6 (488.3)
PAQ-score (1 to 5 scale)	2.6 (0.9) [*]	2.4 (0.7)

[*] p-value < 0.05

[**] p-value < 0.01 from t-test for comparison of male and female subjects

Note: Standard deviation (SD); Peak height velocity (PHV); Bone Strength Index (BSI); polar Strength-Strain Index (pSSI); Physical Activity Questionnaire (PAQ).

Table 2.

Comparison of tibia bone strength outcomes between interscholastic power sport athletes, low-power sport athletes, and no-power sports subjects[*] (Least Squares Means adjusted for height, weight, years from PHV (maturity))

	No-Power Sports (1) Mean (SE)	**Low-power Sports (2) Mean (SE)**	**High-power Sports (3) Mean (SE)**	**F-test (p-value)**	**1 vs. 2 (p-value)**	**1 vs. 3 (p-value)**	**2 vs. 3 (p-value)**
Males (N=176)	**N = 72**	**N = 79**	**N = 25**				
BSI (mg^2/mm^4)	121.89(3.00)	140.21(2.92)	148.77(5.30)	<.0001	<.0001	<.0001	0.1656
pSSI 66% tibia (mm^3)	2929.18(51.27)	3091.39(50.48)	3217.21(89.55)	0.0096	0.0271	0.0061	0.2288
Cortical content, 66% tibia (mg)	365.24(4.91)	387.91(4.83)	413.01(8.58)	<.0001	0.0014	<.0001	0.0128
Females (N=204)	**N = 89**	**N = 38**	**N = 77**				
BSI (mg^2/mm^4)	93.01(2.01)	99.08(3.04)	104.39(2.16)	0.0009	0.0956	0.0002	0.1614
pSSI, 66% tibia (mm^3)	2159.46(28.50)	2183.49(43.36)	2297.89(31.37)	0.0050	0.6424	0.0015	0.0358
Cortical content, 66% tibia (mg)	304.25(3.21)	314.97(4.88)	324.64(3.53)	0.0002	0.0670	<.0001	0.1142

[*] Questionnaire records closest to bone scan date are used.

P-values for overall significance test for grouping from general linear models and pairwise comparisons for group least squares means (group comparison p-values are reported without adjustment for multiple comparisons, p-values<0.05/3 are statistically significant based on Bonferroni adjustment for multiple comparisons).

Note: Standard error (SE); Peak height velocity (PHV); Bone Strength Index (BSI); polar Strength-Strain Index (pSSI).

Table 3.

Comparison of tibia bone strength outcomes between interscholastic power sport athletes, low-power sport athletes, and no-power sports subjects[*] (Least Squares Means adjusted for height, weight, years from PHV (maturity), and total level of physical activity (PAQ score))

	No-Power Sports (1) Mean (SE)	Low-power Sports (2) Mean (SE)	High-power Sports (3) Mean (SE)	F-test (p-value)	1 vs. 2 (p-value)	1 vs. 3 (p-value)	2 vs. 3 (p-value)
Males (N=176)	**N = 72**	**N = 79**	**N = 25**				
BSI (mg^2/mm^4)	122.62(2.95)	139.63(2.88)	148.46(5.21)	<.0001	<.0001	<.0001	0.1452
pSSI 66% tibia (mm^3)	2937.53(50.90)	3084.33(50.07)	3214.35(88.64)	0.0150	0.0441	0.0078	0.2091
Cortical content, 66% tibia (mg)	366.28(4.83)	387.03(4.75)	412.65(8.41)	<.0001	0.0029	<.0001	0.0096
Females (N=204)	**N = 89**	**N = 38**	**N = 77**				
BSI (mg^2/mm^4)	94.39(2.01)	98.62(2.98)	103.06(2.15)	0.0185	0.2406	0.0048	0.2314
pSSI 66% tibia (mm^3)	2169.81(29.02)	2179.39(43.22)	2287.77(31.79)	0.0215	0.8544	0.0088	0.0460
Cortical content, 66% tibia (mg)	306.62(3.19)	314.03(4.75)	322.32(3.50)	0.0067	0.1974	0.0016	0.1638

[*] Questionnaire records closest to bone scan date were used.

P-values for overall significance F-test for grouping from general linear models and pairwise comparisons for group least squares means (group comparison p-values are reported without adjustment for multiple comparisons, p-values<0.05/3 are statistically significant based on Bonferroni adjustment for multiple comparisons).

Note: Standard error (SE); Peak height velocity (PHV); Bone Strength Index (BSI); polar Strength-Strain Index (pSSI).