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Contribution of High School Sport Participation to Young Adult Bone Strength

Ryan C. Ward[1], **Kathleen F. Janz**[1], **Elena M. Letuchy**[2], **Clayton Peterson**[1], **Steven M. Levy**[3]

[1]Department of Health and Human Physiology, College of Liberal Arts and Sciences, University of Iowa, Iowa City, IA;

[2]Department of Epidemiology, College of Public Health, University of Iowa, Iowa City, IA;

[3]Department of Preventative and Community Dentistry, College of Dentistry, University of Iowa, Iowa City, IA.

Abstract

Introduction: Nearly 8 million American adolescents participate in sports. Participation declines in young adulthood.

Purpose: This study assessed longitudinal effects of high school sport participation and muscle power on young adult bone strength.

Methods: 228 young adults from the Iowa Bone Development Study completed an interscholastic sport participation questionnaire. Current physical activity (PA) behaviors were assessed via questionnaire. Dual x-ray absorptiometry (DXA) assessed hip areal bone mineral density (aBMD) and was used with Hip Structure Analysis (HSA) to estimate femoral neck section modulus (FN Z) and hip cross-sectional area (CSA). Peripheral quantitative computed tomography (pQCT) provided strength-strain index (SSIp) and bone strength index (BSI) at 38% and 4% midshaft tibial sites respectively. Vertical jump estimated muscle power at age 17. Gender-specific multiple linear regression predicted young adult bone outcomes based on sport participation groups. Mediation analysis analyzed effects of muscle power on relationships between sport participation and bone strength.

Results: At follow-up, males participating in any interscholastic sport had greater bone strength than males who did not participate in sport. The explained variability in bone outcomes was 2 to 16%. Females who participated in sports requiring muscle power had greater bone strength than females who did not participate in sports or females who participated in non-power sports (explained variability was 4 to 10%). Muscle power mediated 24.7 to 41% of the effect of sport participation on bone outcomes in males.

Conclusion: Former male interscholastic sport participants and female interscholastic power sport participants have stronger bones than peers even when adjusting for current PA. Muscle power did not fully explain differences in all bone outcomes suggesting that sport participation has additional bone health benefits.

Address for correspondence: Kathleen F. Janz, Ed.D.. F.A.C.S.M., E130 Field House University of Iowa, Iowa City, IA 52242; Kathleen-janz@uiowa.edu.

Keywords

Athletics; Bone Structure; Bone Geometry; Muscle Power; Vertical Jump

INTRODUCTION

Bone strength can be defined as resistance to fracture and is a key indicator of bone health throughout the lifespan. In clinical and epidemiological studies, bone strength is approximated using measures of bone mass and bone structure (1). Common methods of assessing mass and structure include dual-energy x-ray absorptiometry (DXA) and peripheral quantitative computed tomography (pQCT). DXA uses two-dimensional imaging to measure areal bone mineral density (aBMD) and bone mineral content. When paired with bioengineering software, DXA can provide further information on the quality of bone. One example of this pairing is hip structure analysis (HSA). HSA uses the distribution of mineral mass that lies in a transverse plane to the bone to measure geometric characteristics at that location (2). From there, further indices of bone strength can be derived such as section modulus, which is an indicator of bending resistance in cross section. pQCT, on the other hand, uses three dimensional images of the bone to measure volumetric bone mineral density (vBMD) and to derive indices of structure including bone strength index (BSI), a measure of bone compressive strength. Strength strain index (SSIp), an estimate of bone resistance to torsion, can also be derived using pQCT (1). Together, these bone outcomes provide important in vivo information on fracture risk.

In addition to other determinants (such as dietary patterns and genetics), physical activity is causally related to bone strength (3,4). Experimental animal studies and randomized control trials indicate that the most beneficial physical activities for bone are dynamic, short in duration, applied quickly, and are high in load magnitude (5,6). For example, Robling et al. have demonstrated in rat models that bone is more responsive short, intermittent activity bouts compared to a single longer bout, emphasizing the importance of activities that are brief in nature (7). Another rat study displayed the importance of the aspects of quick application and high load magnitudes. Järvinen et al. found that rats exposed to mill walking and sudden impacts had higher cross-sectional moment of inertia values, a measure used to calculate bending stress, compared to sedentary animals or animals that only walked (8). In humans, high load magnitudes are delivered to bone during forceful contacts with the ground or other objects (i.e. impact loading) (9). These loads serve as a signal to induce bone adaptations, and commonly occur during jumping, sprinting, or racquet sports (10,11,12). Importantly, high load magnitudes are also applied when muscle rapidly pulls on bone, such as during power lifting (13) or the up-phase of jumping (14). On the other hand, activities without loads, such as cycling, are not effective at strengthening bone (15).

Sport is widely accessible to children and adolescents through educational institutions. The National Federation of State High School Associations reports 7.9 million interscholastic high school sport participants for the 2016–2017 school year (16). Many types of sport expose participants' bones to both impact and muscle forces (17) making it a valuable method of developing bone strength. Both adolescent and young adult athletes that participate in sports such as basketball, soccer, or gymnastics have stronger bones compared to those that participate in non-impact sports or sedentary peers (15,18,19,20). In addition to sport participation, physical fitness, specifically muscle power, has been shown to be predictive of markers of bone strength (21,22).

Although it is common to classify osteogenic activities and sports into weight bearing (17) or impact (19,20) categories, focusing on sports that primarily emphasize muscle power, for example basketball or volleyball, may be more advantageous. Athletes in these sports may train for muscle power by jump training or explosive weight-lifting. By doing so, they expose their bones to both rapidly applied muscle forces and ground impacts while bettering their performance. On the other hand, impact training, such as repeated box step offs, has no power benefits. In addition, muscle power can be tested in a field setting with a vertical jump (22), whereas impact testing requires laboratory equipment. Therefore, by getting coaches, instructors, parents, and athletes to support the notion of muscle power, participants increase sport performance with the bonus of improved bone strength.

Late adolescence and young adulthood are important osteogenic time periods because clinically-relevant bone sites achieve peak mass accrual and ultimately peak bone strength, during this time (23). Regrettably PA, including participation in sport, decreases from adolescence to young adulthood (24). Consequently, exposure to bone strengthening PA is reduced for many young adults. Therefore, there is value in understanding if bone health benefits associated with sport participation during high school are sustained during young adulthood. To this end, using a longitudinal design and a two-year follow up, we examined the amount of explained variability in young adult bone strength attributed to high school interscholastic sport participation. To better understand how sport contributes to bone health, we tested the potential mediating effect of muscle power on the relationship between high school interscholastic sport participation and young adult bone strength. We hypothesized that interscholastic sport participation during high school would positively predict bone strength in the young adults and that much of the association could be explained by muscle power.

METHODS

Participant Recruitment and Study Design

The Iowa Bone Development Study (IBDS) is an ongoing, longitudinal study of bone health and health status from childhood through adolescence and young adulthood. Participants for the IBDS were recruited from 1998 to 2001, when subjects were approximately 5 years of age, from a larger group of children (n = 890) that were already participating in the Iowa Fluoride Study. Recruitment for the Iowa Fluoride Study occurred in eight Iowa hospitals between 1992–1994 immediately following birth. Demographic characteristics of the IBDS subject population include being 95% white, with two-thirds of subjects' parents having college degrees (4). Further information about participants' demographic data has previously been discussed (25). This secondary analysis focuses on IBDS participants with assessments during late adolescence and young adulthood, specifically 18 to 21-year-old males and females (mean age 19.7 years old). The Iowa Bone Development Study was approved by the University of Iowa Institutional Review Board (Human Subjects). Minors provided informed written assent with legal caregivers and subjects over the age of 18 provided informed written consent. Descriptive statistics of the study participants are shown in Table 1.

Body Height, Weight, and Peak Height Velocity

Research staff trained in anthropometry assessed participants' body height (cm) and body weight (kg) using standardized protocols. Body height was measured using a Harpenden stadiometer (Holtain Ltd, Crosswell, UK), and body weight was measured using a Healthometer physician's scale (Continental, Bridgeview, IL). Participants were weighed and measured without shoes, and data were recorded in tenths of kilograms and in tenths of centimeters, respectively. Maturity offset (years from peak height velocity [PHV]) prediction equations established by Mirwald et al. (26) were used to determine somatic maturity. These equations include age, sex, weight, height, sitting height, and leg length as predictors. Peak height velocity estimates were calculated for all participants using ages 11 and 13 examination data for girls and ages 13 and 15 data for boys, if available. The clinical examination (between ages 11 and 15), which provided an estimate of PHV age that was closest to the actual clinical examination age was used as the best estimate (the Mirwald equation is most precise closest to actual PHV age). If only one PHV estimate was available, it was used. As the cohort aged, years since PHV was used as a measure of biological age.

Questionnaire Assessment of Sport Participation

At approximately age 17 years, participants reported the amount and type of high school interscholastic sport participation. Based on the ground reaction forces and peak strain scores associated with different sport participation (27) and investigator knowledge of sport mechanics, high school sport participation groups were coded as Power Sport Participant (PSP) (member of basketball, cheerleading/poms, football, gymnastics, soccer, and/or volleyball team for at least two seasons), Other Sport Participant (OSP) (member of baseball, cross country/track and field, softball, tennis, and/or wrestling team for at least two seasons or power sport participant for one season), or Nonparticipant (NP) (not a member of a high school power sport team, or one season of other sport, or no reported interscholastic sport participation). Since bone intervention studies suggest that a minimum of seven months is needed for bone adaption (1), we required at least two seasons in a sport that we considered to emphasize power to code a participant as PSP. Previous work from our group (Ward, Ryan C.; Janz, Kathleen F.; Letuchy, Elena M.; Peterson, Clayton; Levy, Steven M. Contribution of High School Sport Participation to Young Adult Bone Strength. 2018. Located at: ProQuest Dissertations Publishing, Number 10748928.) used this classification scheme.

Questionnaire Assessment of Physical Activity Behaviors

At follow up, approximately age 19, participants completed the Physical Activity Questionnaire for Adults (PAQ-AD). The PAQ-AD is a seven-day recall questionnaire that asks about general PA, sport participation, exercise, and the intensity of these activities. The PAQ-AD has been shown to be a valid measure of PA when compared to accelerometer measurements of PA (28). The PAQ-AD asks participants about physical activity behaviors using a 1–5 scale with 5 corresponding to higher amounts of activity. Participants' responses to the questions are averaged to give a composite score from 1 to 5. The PAQ-AD was used to adjust all multi-variate analyses for current PA.

Vertical Jump Assessment of Muscle Power

At approximately age 17 years old, participants completed a vertical jump test to test lower body power. Jump height was measured using a Vertec (Questek Corp, Elgin, IL) which has been validated and is strongly correlated (r=0.91) with vertical jump height quantified by a 3-camera motion analyses system (29). We used the Sayers et al. equation to predict muscle power using vertical jump height. The Sayers equation is as follows: (W) = (60.7) × (jump height [cm]) + 45.3 × (body mass [kg] − 2055) (30). This equation uses body weight in part to estimate muscle power and has been validated by comparing estimated muscle power to force platform measured muscle power (Predicted Residual Sum of Squares R^2=0.87) (30). Participants were instructed to perform a squat jump by bending their knees and moving their arms behind them until their knuckles faced the floor, pausing in this squat position so as not to gain any momentum and then jumping as high as possible while reaching up and hitting the Vertec with the dominant arm. After a warm-up, three jumps were measured, and the highest jump height (cm) was recorded.

Dual X-Ray Absorptiometry (DXA) Measurement of Bone Strength

At approximately age 19 years old, trained research staff conducted DXA scans for all participants using the Hologic QDR 4500A DXA (Delphi upgrade) with software V.12.3 in the fan-beam mode, as described previously (4). Briefly, software-specific Global Regions of Interest (ROI) were used to designate the general boundaries of the hip images. The operator reviewed, edited, and confirmed the bone within the ROI box to ensure appropriate bone-edge detection. The DXA measure used in this study was aBMD (g/cm^2) at the total hip. Structural geometry was estimated from hip DXA images using the Hip Structure Analysis program (Hologic Apex 3.0 software). This program is based on the principle first described by Martin and Burr that the mass in a pixel value (g/cm^2 of hydroxyapatite) can be converted to linear thickness (cm) by dividing it by the effective mineral density of a fully mineralized bone (31). A line of pixels traversing the bone axis is thus a projection of the surface area of a bone in cross-section and can yield some of its geometry (2). Specifically, the Hologic software program located the narrowest point of the femoral neck, where bone cross-sectional area (CSA, cm^2) and cross-sectional moment of inertia (cm^4) for bending in the image plane were calculated, from which femoral neck section modulus (FN Z, cm^3) was derived.

Peripheral Quantitative Computed Tomography (pQCT) Measurement of Bone Strength

Tibial measures were acquired using pQCT, software version XCT 6.00 (XCT 2000 or 3000, Stratec, Inc, Pforzheim, Germany), with the Stratec XCT 3000 being used for individuals with a calf circumference greater than 15.5 inches (n = 27). An IBDS calibration study found good agreement between these Stratec models (4). All pQCT scans were acquired by one of three International Society for Clinical Densitometry (ISCD)–certified bone densitometry technologists, and manufacturer-supplied hydroxyapatite phantoms for pQCT were scanned daily for quality assurance. Before scanning, trained technicians used a standard ruler to measure tibial length (mm) from the center of the medial malleolus to the proximal tibial plateau, with the participant resting the lateral side of the foot on the opposite knee. This value was entered into the scanner to standardize the regions of interest as percentages of individual tibia 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, or in cases when the growth plate was no longer visible, the medial side of the distal endplate. Moving proximally from the reference line, the scanner was programmed to acquire measures at 4% and 38% of the tibia length, with all pQCT scans acquired using a voxel size of 0.4mm, a 2.2mm tomographic slice thickness, and a scan speed of 20mm/s (32,4).

Bone strength index (mg^2/mm^4), a measure of bone compressive strength, was estimated from total bone measures at the 4% metaphyseal cross-sectional site using interactive contour search mode 3, with the threshold set just above 169 mg/cm^3 in order to separate soft tissue from bone tissue and generate a volumetric total bone density outcome. BSI was calculated with the following formula: BSI (mg^2/mm^4) = total area (mm^2) × (total density (mg/mm^3)^2) (4). Analyses of the 38% cross-sectional site were used when measuring density weighted polar section modulus strength-strain index (SSIp, mm^3), a measure of torsional strength. Cortmode 2 with a threshold of 480 mg/cm^3 was used for SSIp, as this is the software default threshold for the strength–strain indices.

Statistical Analyses

Study participants were stratified based on sex and sex-specific means and standard deviations were calculated to describe participants. The Student *t*-test was used to compare female and male mean values. Multiple linear regression was used to predict young adult bone outcomes for males and females separately using height, weight, and high school interscholastic sport group classification as explanatory variables after adjusting for current PA. ANOVA with least squares means was performed to determine whether differences in bone outcomes existed between the sex-specific interscholastic high school sport groups. Percent differences between the significantly different mean bone outcomes for the sport groups were calculated. Finally, mediation analysis was performed to describe the causal sequence between sport participation, muscle power, and bone strength outcome. Mediation assumes a precursor variable (interscholastic high school sport participation) has an effect on a mediating variable (jump height) which affects the outcome variable (bone strength) (33). Height, weight, and PAQ-AD score were included as covariates in the mediation analysis models. Jump height was used rather than Watts because the calculation of Watts included weight and therefore created multi-collinearity in our models. Statistical Analysis System (SAS, Cary, NC), version 9.4, was used for the statistical analyses. $P < 0.05$ was specified as representing statistical significance.

RESULTS

Participants

Data from 228 young adults (126 females, 102 males) were obtained (Table 1). The mean ± SD age of participants at follow-up was 19.9 ± 0.8 for males and 19.8 ± 0.7 for females and was not statistically different among the sexes. As expected, females had a greater biological age than males since, on average, females begin puberty sooner and reach peak-height velocity sooner than males (8.0 vs 6.2 years, respectively, $P < 0.01$). Compared to females, males were significantly heavier and taller. Males also had significantly greater values for all bone outcomes ($P < 0.01$). In addition, males had greater vertical jump values ($P < 0.01$) and had greater PAQ-AD scores ($P < 0.01$), indicating greater amounts of lower body power and PA.

There were no differences bone outcomes between male PSPs and OSPs. For females, OSPs were not different than NPs (Table 2). Therefore, we dichotomized our sport groups so that males were categorized as Sport Group 0 (nonparticipant or one season of other sports) or Sport Group 1 (at least 1 season of power sports or 2 seasons of other sports). Females were categorized as Sport Group 0 (nonparticipant or other sport participant or less than 2 seasons of power sports) or Sport Group 1 (at least 2 seasons of power sports). Males had 38 study participants in Sport Group 0 compared to 64 participants in Sport Group 1. Females had 73 and 53 study participants in Sport Group 0 and Sport Group 1 respectively.

Bone Strength Prediction from Multiple Linear Regression

The results from the multiple linear regression models are shown in Table 3. The models for bone outcomes using high school sport group were adjusted for height, weight, and PAQ-AD score. Age and biological were not significant predictors and therefore, were not included in the models. All models used Sport Group 1 classification as a reference (coefficient = 0). The coefficient for Sport Group 0 was significant for all bone outcomes in females (BSI −10.5; SSIp −126.1; aBMD −0.09; FN Z −0.14; CSA −0.24; $P < 0.05$) and males (BSI −21.3; aBMD −0.14; FN Z −0.29; CSA −0.55; $P < 0.05$) with the exception of male SSIp (−136.0 $P = 0.0522$). This indicated that being classified as a Sport Group 0 subject resulted in a lower predicted bone outcome value. PAQ-AD coefficients were significant in all female bone outcomes (BSI 8.65, SSIp 77.68; aBMD 0.04; FN Z 0.13; CSA 0.19; $P < 0.05$), whereas the only PAQ-AD score that was significant for males was for CSA (0.18, $P < 0.05$). The full models explained 34%, 58%, 43%, 53% and 51% of the variance in male bone outcome for BSI, SSIp, aBMD, FN Z, and CSA respectively. Sport group classification specifically accounted for 9%, 2%, 16%, 6%, and 9% of the variability for the same respective bone outcomes. In females, the models explained 41%, 69%, 44%, 69%, and 67% of the variance in BSI, SSIp, aBMD, FN Z, and CSA respectively. Sport group classification accounted for 4%, 3%, 10%, 3%, and 4% of the variability for the same respective bone outcomes.

Mean Differences Among Sport Groups

The results from the ANOVA with least squares means test (Table 4) indicated that Sport Group 1 participants had greater bone outcomes than Sport Group 0 participants, with the exception of male SSIp ($F = 0.052$). The percent differences between the mean bone outcomes are also shown in Table 4. The average percent differences for the mean bone outcomes that were significantly different were 12.2% and 8.3% for males and females respectively.

Mediation Analysis

Table 5 displays the results from the mediation analysis. We found a weak association between female vertical jump and bone outcomes. Therefore, we could not treat vertical jump as a mediator for females and so we only displayed the results from the male models. The direct effects of any sport participation in males (Sport Group 1) were statistically significant ($P < 0.05$) for all bone outcomes with the exception of male SSIp ($P = 0.39$). The bootstrap-derived 95% confidence intervals for the indirect effects of sport participation do not include zero for any of the bone outcomes indicating that muscle power is a mediator between sport group participation and bone strength. Besides male SSIp, the direct effects of sport participation and the direct effects of muscle power are significant. These results indicated that partial mediation had occurred. In the case of male SSIp, muscle power fully mediated increased bone strength.

DISCUSSION

The main purpose of this study was to assess the effect of interscholastic high school sport participation on young adult bone strength. In addition, we performed mediation analysis to analyze muscle power's role in this effect. We found that participating in sports that emphasize powerful movements, such as basketball, volleyball, or gymnastics, predicted young adult indices of bone strength in males and females compared to non-sport participants. In addition, participating in other kinds of sports during high school appears to be as effective as power sports at developing and maintaining bone strength in males. However, females who participated in other sports did not have stronger bones than non-sport participants. Furthermore, in our regression models, we found that PA was a significant predictor of bone strength in females, but not in males. This is contrast to what has previously been reported, as PA has repeatedly been shown to be predictive of bone strength in both males and females (3,4,34). A potential explanation for this anomaly is the fact that males tend to have greater muscle mass than females (35) adding to the load magnitudes that males' bones experience from muscle forces regardless of the amount of activity accrued.

Our results suggest that bone strength associated with high school sport participation is sustained after high school, and presumably, after a reduction in PA. Although we have previously reported that early childhood PA only has limited effects on bone strength during adolescence (36), this current examination focuses on older participants and uses a targeted exposure, namely interscholastic sport participation. Randomized control trials and longitudinal studies of athletes indicate that previous exposure to osteogenic activities leads to maintained bone strength. For example, Gunter et al. (10) performed a 7-month long randomized control jumping intervention trial in prepubertal children and found that even 8 years after the intervention had ceased, the intervention group had significantly greater bone mineral content compared to controls. A study of 8 to 15-year-old female gymnasts by Erlandson et al. (37) observed that even ten years post sport participation, former gymnasts had greater indices of bone strength compared to non gymnast age matched controls. Kudlac et al. (38) studied female collegiate gymnasts and reported after a 4-year period post-competition, former gymnasts had decreased bone mineral density values compared to training years, but still had stronger bones than age matched controls. Findings in adolescent and young adult males are similar. Nordstrom et al. (39) researched 17-year-old male ice hockey players, badminton players, and non-sport participant controls for 8 years. During the study, 27 athletes ceased training after a mean time period of 3 years, but still had greater femoral neck, total hip, and humeral bone mineral density values compared to controls at follow-up five years later.

The percent differences in bone strength between our sport classification groups which we report are lower than what has previously been described. For example, Nikander et al. (40) classified female athletes in their early 20's into either a high-impact loading group (volleyball or hurdling) or an odd-impact loading group (squash, soccer, or speed skating) and compared them to non-athletic age-matched controls. Both athletic groups had more than 20% greater indices for femoral neck aBMD, CSA, and section modulus compared to controls. In a study of adolescent males by Lima et al. (19), similar results were obtained. Study subjects who participated in soccer, gymnastics, or basketball were classified as the impact group and were compared to age-matched controls that only participated in PE classes. The impact group had 17% greater lumbar BMD and 13.6% greater femoral neck BMD. Differences in bone strength can also been seen in tennis players' dominant arms compared to nondominant arms. Haapasalo et al. (12) studied 7 to 17-year old female tennis players and categorized them based on Tanner stages. At all maturity stages, the dominant arms of the tennis players had between 1.6% to 15.7% greater proximal humerus and humeral shaft BMD values than the nondominant arms.

Although our reported percent differences are not as robust as other reported differences, they are still noteworthy. For instance, in randomized control trials, a 3 % increase in bone outcome has been used to denote clinically significant increases in strength (1). Furthermore, increases in bone outcomes similar to what we have observed result in significant increases in mechanical loading strength. This is evidenced by rat model studies in which conditioned and non-conditioned murid femora undergo breaking tests. For example, Järvinen et al. found that small, but significant increases in bone geometric properties led to significant increases in three-point bending and compression strength (8). Therefore, minor increases bone outcomes lead to marked practical implications.

Our mediation analysis results indicated that vertical jump, a measure of muscle power, partially mediated increased bone strength, except SSIp, in male athletes. The fact that muscle power did not completely explain bone strength suggests that other characteristics of physical activity during sport are also osteogenic. For example, movement during sport is dynamic and provides atypical bone loading. These characteristics encourage adaptation (39). In addition, most power moves, such as the up-phase in a jump, are followed by impact forces during landing which would also load bone. Therefore, our sports participants were exposed to muscle forces and ground impacts. A potential explanation for muscle power fully mediating SSIp is the fact that this is analyzed by QCT and measures cortical bone (1). As tendons attach to cortical bone, cortical bone directly experiences mechanical forces from muscle contractions, in addition to impact forces, both of which occur during powerful muscle movements.

There were several limitations to our study. The study sample was a homogenous group of Midwestern young adults and was not representative of the entire US. Therefore, caution should be used when trying to apply these results to a more diverse population. In addition, there was a limitation in our high school sport participation questionnaire. For example, we did not query specific events in track and field and therefore, could not distinguish between lower osteogenic sports (i.e. distance running, discuss) and higher osteogenic sports (i.e. sprints, jumps/hurdles). Finally, participants in the Iowa Bone Development Study were not randomly selected and, of course, high school sport participation is not random. Adolescents with larger bodies and stronger bones may be more inclined to participate in power sports than peers. Despite the limitations, our study has strengths. Many studies that address sport participation and bone strength are cross-sectional (11,12,17,19,40). However, by using a longitudinal design which included adjustment for current physical activity, we were better able to isolate the effect of high school sport participation on bone strength. Importantly, we used multiple indicators of bone strength, including 3-dimensional pQCT imaging to capture bone structure as well as mass.

In conclusion, participation in any interscholastic sport may contribute to improved bone strength in males. Whereas in females, high school participation in power sports is preferred. Although muscle power clearly contributes to bone strength, other factors associated with sport also contribute. Our results suggest that educational institutions promote sport participation for all students as means to achieve a strong skeleton.

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TABLE 1.

Descriptive statistics and sex comparisons.

	Males (N=102)	Females (N=126)	P
Age (yr)	19.9 (0.8)	19.8 (0.7)	0.458
Biological Age (yr since age at PHV)	6.2 (1.1)	8.0 (0.9)	<.001
Weight (kg)	85.4 (21.5)	70.1 (18.1)	<.001
Height (cm)	179.6 (7.8)	166.3 (7.3)	<.001
Tibial 4% BSI (mg^2/mm^4)	148.30 (32.8)	100.6 (23.8)	<.001
Tibial 38% SSIp (mm^3)	2183.8 (490.8	1552.5 (338.2)	<.001
Hip aBMD (g/cm^2)	1.2 (0.2)	1.0 (0.1)	<.001
Femoral Neck CSA (cm^2)	2.32 (0.6)	1.5 (0.4)	<.001
Femoral Neck FN Z (cm^3)	4.4 (0.9)	3.3 (0.6)	<.001
Anaerobic Power output (W)	5001.6 (984.0)	3486.0 (804.1)	<.001
Vertical Jump (cm)	56.1 (10.5)	42.4 (8.4)	<.001
PAQ-AD score	2.4 (0.8)	2.1 (0.7)	<.001
High School Sports			
PSP N (%)	48 (47.1)	53 (42.1)	
OSP N (%)	16 (15.7)	31 (24.6)	
NP N (%)	38 (37.3)	42 (33.3)	
Sport Group 1 N (%)	64 (62.7)	53 (42.1)	
Sport Group 2 N (%)	38 (37.3)	73 (57.9)	

Data are mean ± SD.

PHV, peak height velocity; BSI, bone strength index; SSIp, density weighted polar section modulus strength-strain index; aBMD, areal bone mineral density; CSA, cross sectional area; FN Z, femoral neck section modulus; W, watts; PAQ-AD, physical activity questionnaire for adults; PSP, power sport participant; OSP, other sport participant; NP, nonparticipant.

TABLE 2.

Bone outcome comparisons between PSPs, OSPs, and NPs.

	F[a]	NP	OSP	PSP	NP vs OSP[b]	NP vs PSP[b]	OSP vs PSP[b]
Males (N=102)		**N=38**	**N=16**	**N=48**			
BSI	0.0020	134.7 (4.7)	152.3 (6.9)	157.2 (4.0)	0.038	<.001	0.543
SSIp	0.0310	2098.0 (53.5)	2108.3 (81.0)	2276.8 (47.1)	0.917	0.015	0.074
Hip aBMD	<.0001	1.1 (0.1)	1.2 (0.1)	1.2 (0.02)	0.003	<.001	0.502
FN Z	0.0031	2.1 (0.1)	2.4 (0.1)	2.5 (0.1)	0.049	<.001	0.584
Hip CSA	0.0004	4.0 (0.1)	4.5 (0.2)	4.6 (0.1)	0.010	<.001	0.736
Females (N=126)		**N=42**	**N=31**	**N=53**			
BSI	0.0119	95.2 (3.0)	97.52 (3.42)	106.69 (2.62)	0.615	<.001	0.037
SSIp	0.0022	1485.8 (30.3)	1517.7 (35.0)	1625.8 (26.8)	0.496	<.001	0.017
Hip aBMD	<.0001	0.99 (0.02)	0.99 (0.02)	1.08 (0.01)	0.792	<.001	<.001
FN Z	0.0008	1.4 (0.03)	1.5 (0.04)	1.6 (0.03)	0.090	<.001	0.075
Hip CSA	0.0008	3.2 (0.06)	3.3 (0.06)	3.4 (0.05)	0.246	<.001	0.024

[a]F-test p-value for overall significance of high school sport group comparisons.

[b]P value for sport group comparison.

Outcomes are Mean (SE).

BSI, bone strength index; SSIp, density weighted polar section modulus strength-strain index; aBMD, areal bone mineral density; FN Z, femoral neck section modulus; CSA, cross sectional area; PSP, power sport participant; OSP, other sport participant; NP, nonparticipant.

TABLE 3.

Regression models for bone outcomes

		Males				Females			
Outcome	**Parameter**	**Estimate**	**SE**	**P**	**R-Square R-square change***	**Estimate**	**SE**	**P**	**R-Square R-square change***
BSI	Intercept	−12.25	66.770	0.855	0.34	−9.926	41.126	0.810	0.41
	Height (cm)	0.642	0.386	0.099		0.327	0.261	0.212	
	Weight (kg)	0.552	0.137	<.001		0.632	0.102	<.001	
	PAQ-AD score	2.376	3.645	0.516		8.651	2.413	0.001	
	Sport Group 0	−21.30	5.900	0.001	0.09*	−10.47	3.492	0.003	0.04*
	Sport Group 1	0.0000				0.0000			
SSIp	Intercept	−3404	781.27	<.001	0.58	−2107	421.05	<.001	0.69
	Height (cm)	26.757	4.449	<.001		17.303	2.674	<.001	
	Weight (kg)	10.511	1.606	<.001		9.914	1.046	<.001	
	PAQ-AD score	−27.19	42.583	0.525		77.678	24.702	0.002	
	Sport Group 0	−136.0	69.214	0.052	0.02*	−126.1	35.751	0.001	0.03*
	Sport Group 1	0.0000				0.0000			
Hip aBMD	Intercept	0.839	0.300	0.006	0.43	0.452	0.224	0.045	0.44
	Height (cm)	0.000	0.002	0.898		0.002	0.001	0.180	
	Weight (kg)	0.004	0.001	<.001		0.003	0.001	<.001	
	PAQ-AD score	0.017	0.017	0.309		0.035	0.013	0.009	
	Sport Group 0	−0.137	0.027	<.001	0.16*	−0.089	0.019	<.001	0.10*
	Sport Group 1	0.0000				0.0000			
FN Z	Intercept	−3.690	0.935	<.001	0.53	−2.650	0.473	<.001	0.69
	Height (cm)	0.028	0.005	<.001		0.020	0.003	<.001	
	Weight (kg)	0.010	0.002	<.001		0.011	0.001	<.001	
	PAQ-AD score	0.098	0.053	0.067		0.128	0.028	<.001	
	Sport Group 0	−0.290	0.084	0.001	0.06*	−0.139	0.040	0.001	0.03*
	Sport Group 1	0.0000				0.0000			
Hip CSA	Intercept	−2.057	1.481	0.168	0.51	−1.40	0.778	0.075	0.67
	Height (cm)	0.026	0.008	0.003		0.018	0.005	<.001	
	Weight (kg)	0.018	0.003	<.001		0.021	0.002	<.001	
	PAQ-AD score	0.177	0.083	0.036		0.186	0.048	<.001	
	Sport Group 0	−0.552	0.132	<.001	0.09*	−.244	0.06	<.001	0.04*
	Sport Group 1	0.0000				0.0000			

R Square reflects the variability in bone outcome explained by the model. R-square change* signifies percent of the variability explained by sport group classification. Covariates included in analysis: weight, height, and PAQ-AD score.

BSI, bone strength index; SSIp, density weighted polar section modulus strength-strain index; aBMD, areal bone mineral density; FN Z, femoral neck section modulus; CSA, cross sectional area; PAQ-AD, Physical Activity Questionnaire for Adults.

TABLE 4.

Bone outcome comparisons between Sport Group 0 and Sport Group 1.

	Males (N=102)				Females (N=126)			
Bone Outcome	**F[a]**	**Sport Group 0**	**Sport Group 1**	**% Difference**	**F[a]**	**Sport Group 0**	**Sport Group 1**	**% Difference**
		N=38	**N=64**			**N=73**	**N=53**	
BSI	<.001	134.7 (4.7)	156.0 (3.5)	13.7	<.001	96.2 (2.2)	106.7 (2.6)	9.8
SSIp	0.0522	2098.4 (54.1)	2234.5 (41.3)	NS	<.001	1499.5 (22.7)	1625.6 (26.8)	7.8
Hip aBMD	<.001	1.1 (0.02)	1.2 (0.02)	11.4	<.001	1.0 (0.01)	1.1 (0.01)	8.3
FN Z	<.001	2.1 (0.1)	2.4 (0.1)	11.9	<.001	1.5 (0.03)	1.6 (0.03)	8.6
Hip CSA	<.001	4.0 (0.1)	4.6 (0.1)	12.0	<.001	3.2 (0.04)	3.4 (0.1)	7.0

[a]F-test p-value for overall significance of high school sport group comparisons.

BSI, bone strength index; SSIp, density weighted polar section modulus strength-strain index; aBMD, areal bone mineral density; FN Z, femoral neck section modulus; CSA, cross sectional area; NS, not significant.

TABLE 5.

Mediation analysis for male bone outcomes.

	β	SE	P
BSI (mg^2/mm^4)			
Sport Group to VJ (a path)	6.964	1.861	<.001
Direct Effects of VJ on BSI (b path)	1.254	0.300	<.001
Total effect of Sport Group on BSI (c path)	21.298	5.900	<.001
Direct Effect of Sport Group on BSI (c' path)	12.568	5.836	0.034
Indirect Effects of Sport Group on BSI through VJ (ab)*	8.733	3.257	**41.0%***
Bias-corrected 95% CI from bootstrapping	3.583	16.839	.
SSIp (mm^3)			
Sport Group to VJ (a path)	6.523	1.840	<.001
Direct Effects of VJ on SSIp (b path)	11.540	3.654	0.002
Total effect of Sport Group on SSIp (c path)	136.021	69.214	0.052
Direct Effect of Sport Group on SSIp (c' path)	60.752	70.377	0.390
Indirect Effects of Sport Group on SSIp through VJ (ab)*	75.269	34.079	**55.3%***
Bias-corrected 95% CI from bootstrapping	22.659	158.15	.
Hip aBMD (g/cm^2)			
Sport Group to VJ (a path)	6.628	1.877	<.001
Direct Effects of VJ on aBMD (b path)	0.005	0.001	<.001
Total effect of Sport Group on aBMD (c path)	0.137	0.027	<.001
Direct Effect of Sport Group on aBMD (c' path)	0.103	0.027	<.001
Indirect Effects of Sport Group on aBMD through VJ (ab)*	0.034	0.015	**24.7%***
Bias-corrected 95% CI from bootstrapping	0.012	0.073	.
FN Z (cm^3)			
Sport Group to VJ (a path)	6.628	1.877	<.001
Direct Effects of VJ on BSI (b path)	0.015	0.004	<.001
Total effect of Sport Group on FN Z (c path)	0.290	0.084	<.001
Direct Effect of Sport Group on FN Z (c' path)	0.191	0.084	0.026
Indirect Effects of Sport Group on FN Z through VJ (ab)*	0.100	0.045	**34.4%***
Bias-corrected 95% CI from bootstrapping	0.036	0.221	.
Hip CSA (cm^2)			
Sport Group to VJ (a path)	6.628	1.877	<.001
Direct Effects of VJ on CSA (b path)	0.026	0.007	<.001
Total effect of Sport Group on CSA (c path)	0.552	0.132	<.001
Direct Effect of Sport Group on CSA (c' path)	0.380	0.132	0.005
Indirect Effects of Sport Group on CSA through VJ (ab)*	0.172	0.070	**31.2%***
Bias-corrected 95% CI from bootstrapping	0.061	0.360	.

* indicates % of bone outcome mediated by muscle power.

Covariates included in analysis: weight, height, and PAQ-AD score.

BSI, bone strength index; SSIp, density weighted polar section modulus strength-strain index; aBMD, areal bone mineral density; CSA, cross sectional area; FN Z, femoral neck section modulus.