Muscle Power Predicts Adolescent Bone Strength: Iowa Bone Development Study

KATHLEEN F. JANZ[1,2], ELENA M. LETUCHY[2], TRUDY L. BURNS[2], SHELBY L. FRANCIS[1], and STEVEN M. LEVY[2,3]

[1]Department of Health and Human Physiology, College of Liberal Arts and Sciences, University of Iowa, Ames, IA; [2]Department of Epidemiology, College of Public Health, University of Iowa, Ames, IA; and [3]Department of Preventive and Community Dentistry, College of Dentistry, University of Iowa, Ames, IA

ABSTRACT

JANZ, K. F., E. M. LETUCHY, T. L. BURNS, S. L. FRANCIS, and S. M. LEVY. Muscle Power Predicts Adolescent Bone Strength: Iowa Bone Development Study. *Med. Sci. Sports Exerc.*, Vol. 47, No. 10, pp. 2201–2206, 2015. **Purpose**: To assess association between lower body muscle power and bone strength as well as the mediating effect of muscle cross-sectional area (MCSA) on that association. **Methods**: Participants (141 males and 162 females) were approximately 17 yr. Muscle power was predicted using vertical jump and the Sayers equation. Using peripheral quantitative computed tomography (pQCT), bone strength indices were obtained at two locations of the tibia, corresponding to primary stressors acting upon each site: bone strength index for compression (BSI) at the distal 4% site; density-weighted polar section modulus strength–strain index (SSIp) and cortical bone area (CoA) at the 66% midshaft site for torsion. Muscle cross-sectional area was measured at the 66% site. Pearson bivariate and partial correlation coefficients were estimated to quantify the strength of the associations among variables. Direct and indirect mediation model effects were estimated, and 95% bootstrap confidence intervals were constructed to test the causal hypothesis. Height and maturity were examined as covariates. **Results**: Pearson correlation coefficients among muscle power, MCSA, and bone strength were statistically significant ($P < 0.01$) and ranged from $r = 0.54$ to $r = 0.78$. After adjustment for covariates, associations were reduced ($r = 0.37$ to 0.69) ($P < 0.01$). Mediation models for males for BSI, SSIp, and CoA accounted for 38%, 66%, and 54% of the variance in bone strength, respectively. Models for females for BSI, SSIp, and CoA accounted for 46%, 77%, and 66% of the variance, respectively. **Conclusions**: We found strong and consistent associations as well as direct and indirect pathways, among muscle power, MCSA, and tibia strength. These results support the use of muscle power as a component of health-related fitness in bone health interventions for older adolescents. **Key Words:** ADOLESCENT, BONE GEOMETRY, BONE STRUCTURE, SKELETON, VERTICAL JUMP

Physical activity is recommended as one of the most effective strategies for promoting a healthy, strong skeleton in children and adolescents. During activity, muscle forces account for most bone strains leading to structural adaptation, resulting in increases in bone strength (24). This connection between muscle force and bone strength is summarized in Harold Frost's mechanostat theory (6), indicating that the greater the force on the bone by muscles, the greater the bone adaptation.

To more directly understand how bone adapts to the loading characteristics of physical activity, measurement methods that provide accurate assessments of both bone strength and muscle function must be used. Advances in bone imaging (peripheral quantitative computed tomography [pQCT]) provide quantitative measures of whole bone strength indices along the length of the tibia, corresponding to primary stressors acting on various sites, including bone strength index (BSI; primarily a measure of strength during compression), density-weighted polar section modulus (stress–strain index [SSIp]), a measure of torsional strength, and cortical bone area (CoA), which exponentially increases SSIp (1). However, assessment of direct muscle function is less common. Studies (14,15,26,27) examining muscle–bone relationships often use muscle cross-sectional area (MCSA) as a surrogate of muscle function. These studies report MCSA as a strong and consistent predictor of bone strength (14,15,26,27). However, the assessment of MCSA requires clinical imaging, which is expensive, and some imaging techniques include radiation exposure. In addition, MCSA is a measure of size, not function; it does not fully reflect muscle quality, e.g., contractile and neuromuscular integrity properties (6,24). These properties are influenced by physical activity, suggesting that muscle function can serve as a proxy for the cumulative effects of bone-enhancing physical activity. This is similar to how aerobic fitness serves as a proxy for the cumulative effects of cardiovascular-enhancing physical activity. Muscle power can be measured noninvasively via force plates, isokinetic dynamometry, Wingate testing, or field tests such as the vertical and long jumps (3). If the associations between bone strength and an easy-to-measure test of muscle power

Address for correspondence: Kathleen F. Janz, Ed.D., F.A.C.S.M., E130 Field House University of Iowa, Iowa City, IA 52242; E-mail: kathleen-janz@uiowa.edu.
Submitted for publication August 2014.
Accepted for publication February 2015.

0195-9131/15/4710-2201/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000000648

are strong and consistent, muscle power could be used in health promotion programming, in health-related fitness assessments, and as an outcome in exercise interventions aimed at improving bone health.

Few studies examining the influence of physical activity on bone strength in older adolescents exist; and, to the best of our knowledge, no studies have specifically assessed physical activities that increase muscle power in relation to bone strength during late adolescence. However, an observational cross-sectional study of males and females ranging from 15 to 20 yr of age conducted by McKay et al. (18) identified a significant, positive relationship between sports and physical activities designated as impact loading (e.g., all activities that involve running) and both minimal and maximal cross-sectional moments of inertia of the tibia in males (explaining 10% and 12% of the variance, respectively). No significant relationship was seen for females by McKay et al. (18). A study by Greene et al. (7) reported that BSI was higher in female middle-distance running athletes (13–18 yr) compared to female nonathletes, with physical activity being the greatest predictor of BSI. A recent systematic review and narrative synthesis conducted by Tan et al. (28) investigated the influence of physical activity on bone strength in children and adolescents (age 5–18 yr). Tan et al. (28) report that physical activity–related changes in bone structure, rather than bone mass, most often accompanied significant changes in bone strength. The authors also noted that muscle mediated the relationship of physical activity to bone (28).

The purpose of this study was to assess the association between lower body muscle power and measures of bone strength of the distal and proximal tibia: BSI (strength during compression) and SSIp and CoA (strength during torsion), respectively. We sought to elucidate the mediation pathway of muscle power, MCSA, and bone strength. We also investigated the use of a field test of muscle power, the vertical jump, to predict bone strength in adolescents.

METHODS

Participants. The Iowa Bone Development Study (IBDS) is an ongoing longitudinal study of bone health during childhood, adolescence, and young adulthood. Information about the study design and demographic characteristics of participants is available in prior publications (10–12). However, in brief, participants were recruited from 1998 to 2001 from a larger group of Midwestern children (n = 890) already participating in the Iowa Fluoride Study. Approximately 95% of the IBDS participants are white and two-thirds of their parents have college degrees. The current analysis focused on data collected when participants were approximately 17 yr of age (141 males and 162 females). The study was approved by the University of Iowa Institutional Review Board (Human Subjects). The parents provided written informed consent, and minors provided assent.

Sample design and data collection. Participants completed a clinical examination that included anthropometry, vertical jump, and pQCT of the lower leg at age 17. Research staff trained in anthropometry measured the participants' weight (kg), standing height (cm), and using standardized protocols, sitting height (cm) at multiple longitudinal assessments. Weight was measured using a Healthometer physician's 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 et al. (20) 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.

Vertical jump. Participants completed a vertical jump test to estimate lower body power (watts [W]). Jump height was quantified using a Vertec (Questek Corp, Elgin, IL), which has been shown to be strongly (r = 0.91) associated with vertical jump height determined by a three-camera motion analysis system (13). The 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 to not 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. The Sayers equation was used to predict muscle power (W) = (60.7) × (jump height [cm]) + 45.3 × (body mass [kg]) − 2055)). This equation has been validated against force platform measures of power in male (mean [SD] age, 21.3 [3.4] yr) and female (mean [SD] age, 20.4 [2.2] yr) athletes and nonathletes (R^2 = 0.87; SEE = 328.4 W) (25).

Peripheral quantitative computed tomography (pQCT). Tibial measures for most of the participants were acquired using pQCT, software version XCT 6.00 (XCT 2000, Stratec, Inc, Pforzheim, Germany). However, the Stratec XCT 3000 was used to acquire measures for the 27 participants who had a calf circumference greater than 15.5 inches, which is too large to fit in the XCT 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 females age 21–58 yr) on both machines within 6 wk 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 area 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, SSIp was determined for cortical bone at the 66% site. The mean difference in SSIp values obtained with the XCT 3000 were less than 2.2% compared with the results from the XCT 2000 machine (unpublished data).

In light of inadequate evidence supporting the use of the dominant versus nondominant limb for the bone and muscle measures (1,31), the left leg was scanned, unless there was a history of fracture (<1% of participants). Before 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 a scan speed of 20 $mm \cdot s^{-1}$. All pQCT scans were acquired by one of 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 $mg \cdot cm^{-3}$. 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 BSI ($mg^2 \cdot mm^{-4}$), was calculated with the following formula: BSI ($mg^2 \cdot mm^{-4}$) = total area (mm^2) × (total density ($mg \cdot mm^{-3}$)^2).

Analyses of the diaphyseal 66% cross section were used to find SSIp, CoA, and MCSA. For SSIp, cort mode 2 with a threshold of 480 $mg \cdot cm^{-3}$ was used, as this is the software default threshold for the strength–strain indices (SSI). SSI is section modulus using bone density as a material property. Each voxel is weighted based on a normal bone density of 1200 $mg \cdot cm^{-3}$ and applied to the equation by dividing each voxel density by 1200 $mg \cdot cm^{-3}$. Bending strength results are reported in the *X* and *Y* plane but are not used because they are dependent on the bone rotation. Strength–strain index is not dependent on rotation and is the preferred result to report. Cortical bone area was measured using separation mode 2 and a threshold of 710 $mg \cdot cm^{-3}$ combined with analysis filtering. The 66% site was also chosen as an optimum location for MCSA (mm^2) assessment. To assess muscle, independent of bone and lower-density soft tissues, an initial threshold of -100 $mg \cdot mm^{-3}$ was used to separate air from skin and define the limb cross section. A slightly higher threshold of 40 $mg \cdot mm^{-3}$ was then applied to separate subcutaneous fat from muscle and bone. An image filter further improved separation of densities to better delineate muscle from fat. To subtract the bone left within the muscle field, a threshold of 710 $mg \cdot cm^{-3}$ was used to define the contour of the bone, then marrow voxels below 40 $mg \cdot cm^{-3}$ were removed to define MCSA.

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 found to have inacceptable levels of movements at any site of interest, imprecise reference line placement, or possible failed muscle loop analysis were excluded (4% of total scans for age 17 participants). Precision analysis has been performed for the 4% radius site on a small sample of participants in the same age group. Two technicians showed high inter-rater reliability with intraclass correlation coefficients (ICC) exceeding 0.98 for all measures tested (total and trabecular area, and 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.

Statistical analysis. Sex-specific means and standard deviations were calculated to describe the distributional properties of the measures. The Student *t*-test was used to compare male and female mean values. Normality probability plots showed no severe departure from normality for variables included in analyses (data not shown). Pearson bivariate and partial correlation coefficients were estimated to quantify the strength of linear associations among muscle power, MCSA, and bone strength outcomes (BSI at 4% site, and SSIp and CoA at 66% site). Partial correlation analysis removed the effect of height and somatic maturity (age from PHV) from the correlation estimates. Mediation analysis was used to characterize a causal sequence of muscle power, MCSA, and bone strength outcomes (16). Mediation assumes that a precursor variable (muscle power) has an effect on a mediating variable (MCSA), which in turn affects the outcome variable (bone strength) (16). Unstandardized and standardized regression parameter estimates were calculated. (In standardized regression, all variables were standardized by sex to *z*-scores with mean = 0 and SD = 1.) Height and somatic maturity (time in years from PHV) were tested as covariates and were retained in the models if statistically significant ($P < 0.05$). Note that weight is a variable in the prediction of watts. In addition, bias-corrected bootstrapping (1000 bootstrap samples) was used to construct 95% confidence intervals to describe the indirect effects of muscle power on bone strength measures (through MCSA) (9). Statistical Analysis System (SAS), version 9.2, was used for the statistical analyses. Mediation analysis was performed using SAS macro % indirect (9,23). $P < 0.05$ was specified as representing statistical significance.

RESULTS

The 303 participants are described in Table 1. The males, when compared to the females, were significantly heavier and taller. They also had greater muscle power and greater

TABLE 1. Participants' characteristics (141 males and 162 females).

	Males Mean (SD)	Females Mean (SD)
Age at scan, yr	17.6 (0.4)*	17.5 (0.4)
Time from PHV, yr	3.9 (0.9)**	5.7 (0.7)
Weight, kg	78.6 (18.2)**	66.2 (16.5)
Height, cm	178.6 (7.5)**	166.0 (6.9)
Muscle power, W	4854 (947)**	3478 (824)
BSI 4% tibia, $mg^2 \cdot mm^{-4}$	134 (31)**	98 (23)
SSIp 66% tibia, mm^3	3034 (687)**	2225 (512)
CoA 66% tibia, mm^2	351.9 (53.3)**	282.0 (41.1)
MCSA 66% tibia, mm^2	8129 (1429)**	6663 (1063)

*$P < 0.05$ and **$P < 0.01$ *t*-test comparing males and females.

bone strength outcomes at both tibia sites than the females. The mean time from PHV for females was significantly longer than for males (5.7 vs 3.9 yr, respectively).

Pearson bivariate and partial correlation coefficients among muscle power, MCSA, and bone strength outcomes are presented in Table 2. All associations were statistically significant ($P < 0.01$). Pearson correlation coefficients with bone outcomes were higher for muscle power and SSIp (r = 0.74, males; and 0.78, females) when compared to muscle power and BSI (r = 0.58, males; and 0.54, females) and muscle power and CoA (r = 0.69, males and females). After removing the effect of height and maturity (time from PHV), the magnitudes of the associations between muscle power and both BSI (r = 0.49, males; and 0.37, females) and SSIp (r = 0.56, males; and 0.62, females) were reduced, but remained highly significant ($P < 0.01$). The magnitudes of the associations between muscle power and CoA remained unchanged. The magnitudes of the associations between muscle power and bone strength outcomes were nearly identical to those for the associations between MCSA and bone strength outcomes.

The mediation analysis results are shown in Table 3. The direct effects of muscle power were statistically significant ($P < 0.001$) for all of the bone strength measures, with the exception of BSI for the females ($P > 0.05$). The standardized β values indicated that the direct effect of muscle power was greater in the males than in the females for BSI and CoA (β = 0.35 vs 0.08, 0.15 vs 0.38 vs 0.15, respectively) but similar between the males and the females for SSIp at the 66% site (β = 0.33 vs 0.33). Each of the mediation models accounted for a higher percentage of the variance in strength outcomes in the females than in the males. For example, the mediation model for BSI accounted for 38% of the variance in the males versus 46% in the females; the model for SSIp at the 66% site accounted for 66% of the variance in the males versus 77% in the females; and the model for COA at the 66% site accounted for 54% of the variance in the males versus 66% in the females. The bootstrap-derived 95% confidence intervals for the indirect effects are also shown in Table 3. None of the confidence intervals included zero, indicating that our finding that MCSA is a mediator between muscle power and bone strength is unlikely to be due to sampling error.

TABLE 2. Bivariate and partial associations for muscle power with bone strength and muscle cross-sectional area

Pearson Correlation Coefficients (*r*)				
	Muscle Power (W)		MCSA 66% Tibia (mm^2)	
	Males	Females	Males	Females
BSI, $mg^2 \cdot mm^{-4}$	0.58	0.54	0.56	0.66
SSIp 66% tibia, mm^3	0.74	0.78	0.68	0.68
CoA 66% tibia, mm^2	0.69	0.69	0.62	0.67
MCSA 66% tibia, mm^2	0.70	0.70		
Partial correlations coefficients with the effect of height and maturity removed (*r*)				
	Muscle power (W)		MCSA 66% tibia (mm^2)	
	Males	Females	Males	Females
BSI, $mg^2 \cdot mm^{-4}$	0.49	0.37	0.42	0.58
SSIp 66% tibia, mm^3	0.56	0.62	0.57	0.61
CoA 66% tibia, mm^2	0.69	0.63	0.64	0.66

All associations significant: $P < 0.01$.

TABLE 3. Mediating effect of muscle cross-sectional area on association of bone strength measures with muscle power

	Males			Females		
	β	SE	β_{STD}	β	SE	β_{STD}
Model for BSI 4% tibia site[a]						
Effect of muscle power on MCSA	0.84**	0.10	0.54	0.86**	0.08	0.65
Effect of MCSA on BSI	0.05*	0.02	0.25	0.12**	0.02	0.53
Total effect of muscle power on BSI	0.16**	0.03	0.48	0.12**	0.02	0.43
Direct effect of muscle power on BSI	0.12**	0.03	0.35	0.02	0.02	0.08
Indirect effect through MCSA	0.04	0.02	0.14	0.10	0.02	0.35
Bias-corrected 95% CI from bootstrapping	(0.01, 0.08)			(0.07, 0.14)		
Model R^2	0.38			0.46		
Model for SSIp 66% tibia site[b]						
Effect of muscle power on MCSA	0.96**	0.11	0.61	0.93**	0.09	0.71
Effect of MCSA on SSIp (66%)	1.72**	0.37	0.33	1.25**	0.27	0.26
Total effect of muscle power on SSIp (66%)	3.73**	0.49	0.53	3.23**	0.32	0.51
Direct effect of muscle power on SSIp (66%)	2.08**	0.58	0.33	2.06**	0.39	0.33
Indirect effect though MCSA	1.66	0.43	0.20	1.16	0.27	0.18
Bias-corrected 95% CI from bootstrapping	(0.83, 2.54)			(0.67, 1.69)		
Model R^2	0.66			0.77		
Model for CoA 66% tibia site[b]						
Effect of muscle power on MCSA	0.96**	0.11	0.61	0.93**	0.09	0.71
Effect of MCSA on CoA (66%)	0.12*	0.03	0.29	0.15**	0.03	0.39
Total effect of muscle power on CoA (66%)	0.31**	0.04	0.55	0.22**	0.03	0.43
Direct effect of muscle power on CoA (66%)	0.21**	0.05	0.38	0.08*	0.04	0.15
Indirect effect though MCSA	0.10	0.03	0.18	0.14	0.03	0.28
Bias-corrected 95% CI from bootstrapping	(0.04, 0.17)			(0.09, 0.21)		
Model R^2	0.54			0.66		

Model parameter β is reported per increase in MCSA = 10 mm^2 and increase in muscle power = 10 W.
[a]Covariate included in analysis: maturity (years from PHV age).
[b]Covariates included in analysis: maturity (years from PHV age) and height (cm).
*$P < 0.05$ and **$P < 0.001$.
β, regression parameter estimate; β_{STD}, standardized regression parameter estimate by sex to *z*-scores (with mean = 0 and SD = 1).

DISCUSSION

The main purpose of this study was to assess associations and pathways between lower body muscle power and bone strength in adolescents. We identified strong and consistent associations as well as direct and indirect pathways between these variables. As expected, associations were stronger at the proximal (shaft) site than the distal site owing to the disadvantageous positioning of muscle attachments on bony levers,

which creates greater physiologic loads than normally expected from gravity (5,21,29). Importantly, the magnitude of the association between muscle power and bone strength was nearly identical to the magnitude of the association between MCSA and bone strength. The direct effect of muscle power on bone strength suggests that muscle function is not synonymous with muscle size. Perhaps the nonmediated effect was due to the integration of high intensity, high frequency, and odd loading movement, which is characteristic of physical activities, where lower body muscle power is more important than lower body muscle size, e.g., playing basketball and volleyball. These movement characteristics have been shown in laboratory studies to predict whole bone adaptation (21,29). On the other hand, the nonmediated effect could be due to the impact loading (e.g., landing during a jump) that occurs during physical activities that require power movements. Future work should attempt to isolate the independent bone-strengthening effects of power movements from impact loading movements.

Our results support the significance of muscle power as a predictor of bone strength. Understanding the role of muscle function on bone strength is important, since it is possible to train for muscle size without increasing muscle power (e.g., isometric contractions) or to increase muscle size via the use of pharmaceuticals (e.g., anabolic steroids). Additionally, measures of muscle power (vertical jump) are less invasive to obtain than clinical measures of muscle size (MCSA). In contrast to our findings, in a study of 6- to 9-yr-old girls, Daly et al. (5) found that lean tissue mass predicts bone strength better than muscle function. However, Malina and Bouchard (17) suggest that young children might lack the physical development to accurately perform a vertical jump. In partial support of our findings, MacDonald et al. (15) found a significant association ($r = 0.18$, $P < 0.05$) between vertical jump height and BSI in their sample of prepubertal and early-pubertal girls (9 to 11 yr), but no significant relationship was seen in the boys ($r = 0.10$, $P > 0.05$). This could be due to a higher percentage of girls in the MacDonald et al. study being more physically developed when compared to the boys or due to some other (unknown) factor (15).

Muscle power is considered a performance-related physical fitness attribute, i.e., important for success in sports (2). As such, it is not assessed in the most commonly used health-related fitness testing programs, such as the Cooper Institute FITNESSGRAM (19). However, our work and the work of others (4,8,22) suggest it is time to consider muscle power as a component of health-related fitness and bone-enhancing health. If our findings are supported in future research with younger and more diverse participants, the vertical jump could add important information to comprehensive assessments of health-related physical fitness and be used to track the success of health promotion programming delivered to optimize bone health. In addition, physical activities that maintain and improve power could be measured in health surveillance systems and targeted in physical activity interventions. At this time, the US physical activity guidelines for Americans (30) explicitly recommend bone-enhancing (also called weight-bearing or weight-loading) physical activities for children and adolescents but does not identify muscle power as a desirable fitness attribute to achieve healthy bone.

Like all studies, this study has limitations. Our cohort is not representative of the general US population. In addition, muscle power and bone strength are both site-dependent factors; therefore, the associations we report for lower body muscle power and bone strength of the tibia might not be the same for other skeletal locations, e.g., the clinically important proximal femur. In addition, most vertical jump tests, including the one we used, do not include a timed component and, therefore, they are not criterion measures of muscle power. Finally, our study was cross-sectional; we had the ability to examine relationships but not cause and effect.

An important strength of our study was the use of a normal, healthy cohort of adolescents, which increased the clinical importance of our findings. In addition, we used an advanced imaging technique, pQCT, to measure bone strength indices and investigated the relationships among MCSA, muscle power, and bone strength. In summary, using a simple test (vertical jump) to measure muscle power, we report a strong and consistent relationship between muscle power and bone strength in adolescents.

This work was supported by the National Institute of Dental and Craniofacial Research (R01-DE12101 and R01-DE09551) and the National Center for Research Resources (UL1 RR024979 and M01-RR00059).

The authors thank the staff of the Iowa Fluoride Study for their organizational efforts, especially our exercise specialists, Ms. Kristen Metcalf and Dr. Joanna Morrissey. The authors likewise thank the Iowa Fluoride Study and the Iowa Bone Development Study participants and their parents; without their contributions, this work would not have been possible.

There are no potential conflicts of interest. The results of the study do not constitute endorsement by the American College of Sports Medicine.

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