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Physical Activity and Femoral Neck Bone Strength during Childhood: The Iowa Bone Development Study

Kathleen F. Janz, Ed.D.[1,2], **Julie M. Eichenberger Gilmore, Ph.D.**[3], **Steven M. Levy, D.D.S., M.P.H.**[3,2], **Elena M. Letuchy, M.S.**[2], **Trudy L. Burns, M.P.H., Ph.D.**[2,4], and **Thomas J. Beck, Sc.D.**[5]

[1]*Department of Health and Sport Studies, The University of Iowa, Iowa City, Iowa* [2]*Department of Epidemiology, The University of Iowa, Iowa City, Iowa* [3]*Department of Preventive and Community Dentistry, The University of Iowa, Iowa City, Iowa* [4]*Department of Pediatrics, The University of Iowa, Iowa City, Iowa* [5]*Department of Radiology, Johns Hopkins University, Baltimore, Maryland*

Abstract

Structural adaptations of bone to changing mechanical loads have recently been documented during adolescence. However, little is known about how bone adapts structurally during the earlier years. Using a longitudinal observational design spanning six years of growth (age range 4 to 12 yr), we investigated associations between everyday physical activity and hip geometry in a cohort of healthy Midwestern children (n = 468). Femoral neck (FN) cross sectional area (CSA, cm^2) and FN section modulus (Z, cm^3) were used to describe hip geometry. CSA and Z, indices of axial and bending strength, were assessed using dual-energy x-ray absorptiometry (DXA) scans and the Hip Structure Analysis (HSA) program. Moderate and vigorous physical activity (MVPA) was assessed using accelerometry-based activity monitors and calculated as the number of minutes ≥ 3,000 accelerometry movement counts. Data were analyzed using multilevel (random- and fixed-effects) regression models with adjustment for age (yr), height (cm), and weight (kg) or lean mass (kg). For boys and girls, MVPA was a positive independent predictor of CSA and Z ($p < 0.05$). On average, children who participated in 40 minutes of MVPA per day would be expected to have 3 to 5% greater CSA and Z than peers participating in 10 minutes of MVPA per day. Ten-minute increases in daily MVPA had similar effects on CSA in girls and Z in boys as did each additional 1 kg of body weight. When lean mass was substituted for weight, MVPA continued to be a positive independent predictor of CSA and Z for boys, but not girls. This study demonstrates that everyday amounts of physical activity in children are associated with indices of FN bone strength during childhood. Differences in lean mass mediate associations between physical activity and hip geometry in girls, but only somewhat in boys. These results suggest that physical activity is an important contributor to bone strength prior to adolescence and that increasing levels of physical activity during childhood are likely to enhance optimal bone strength.

Keywords

accelerometry; bone geometry; exercise; growth; longitudinal study

Correspondence: Kathleen F. Janz, Department of Health and Sport Studies, 102 FH, University of Iowa, Iowa City, IA 52242, (319) 335-9345, Fax: (319) 335-6669, E-Mail: kathleen-janz@uiowa.edu

INTRODUCTION

While it is not always appreciated, bones dynamically adapt to mechanical loads experienced during physical activities by changing geometry and strength, in addition to bone mass. Presumably, the adaptation of bone to mechanical loads adjusts the strength of bone to the current loading conditions that it experiences [5,11]. Mechanical loads imposed on bones during physical activities are directly mediated by muscle forces. In fact, the largest physiologic loads placed on bones are from muscle contractions [29]. These loads are routinely greater than the effect of gravity due to the disadvantageous positioning of muscle attachments on bony levers [29]. This phenomenon, described in the Mechanostat Theory, is particularly evident during periods of skeletal growth, such as childhood [11]. The Mechanostat theory suggests, that when all else is equal, children who are more physically active should have stronger bones than their less active peers [11]. The extent of the response of bones to physical activity during childhood is of considerable importance for the attainment of peak skeletal mass. It is plausible that greater levels of physical activity during critical growth years may lead to long-term skeletal benefits [17,23,30].

Bones break when loading stresses exceed the capacity of the tissue to withstand them. Under a given load, the stresses are determined by the amount and the distribution of bone tissue within bones (structural geometry), while resistance to stress is a function of the bone tissue composition [23,28]. Therefore, the effects of physical activity should be evident in the geometry of bones, and perhaps also, in the material strength of bones, although the latter cannot currently be assessed by non-invasive means [1,24]. Recently, using data from the *Saskatchewan Paediatric Bone and Mineral Accrual Study*, Forwood and colleagues [7] described the time course of geometric change in the proximal femur of normal boys and girls as they traversed puberty. In addition, other investigators have shown the positive effects of exercise interventions on hip geometry [20,25,27]. In our earlier paper [13], we directly measured the dynamic physical activity-related forces on young children (mean age 5 yr) using a small accelerometer-based activity monitor placed above the hip of each child. This work was observational and cross sectional. Our results showed that those children with higher accelerometry-measured movement counts had commensurately stronger proximal femurs [13].

In this report, we extend our analysis by examining longitudinal associations between accelerometry-measured physical activity and hip geometry as children traverse middle- and late-childhood. Given that physical activity is anabolic to muscle, we also examined whether effects of physical activity on bone geometry seem to be mediated by muscle development [26,29].

MATERIALS AND METHODS

Study Population

The study participants were generally healthy Midwestern children recruited during 1998 – 2001 from 890 families then participating in the Iowa Fluoride Study, a longitudinal study of fluoride intake and dental fluorosis [18]. The children's mothers were predominantly white (98%), and of relatively high SES, with 48% of mothers having a 4-year college degree at the time of the child's birth. Physical activity measures and DXA scans were obtained three times during a six-year time span per child. Four hundred thirty-three children had physical activity and bone structure measures at approximately 5 years of age (baseline), 495 at approximately 8 years of age, and 406 at approximately 11 years of age. Data from all visits were combined and children who participated in bone and physical activity studies at only a single time period were eliminated, resulting in 468 children (227 boys and 241 girls) with measures for at least two time periods. Within this group, 127 boys and 162 girls had measures at all three time

periods (for 1225 records total). Almost all (95%) of the children were white. The study was approved by The University of Iowa Institutional Review Board (Human Subjects). Written informed consent was provided by the parents of the children and assent was obtained from the children at the time of each examination.

DXA Measures

At ages 5 and 8, we conducted whole body and left hip scans using a Hologic 2000 dual-energy x-ray bone absorptiometer (DXA) (Hologic, Waltham, MA) with software version 7.20B and pencil-beam mode. At age 11, the Hologic QDR 4500 (Delphi upgrade) with software version 12.3 and fan-beam mode was used for scan acquisition. Total body lean mass (fat-free mass minus BMC in kg), hip BMC (g), bone area (BA in cm^2), and areal bone mineral density (g/cm^2) were derived from the scan images. Quality control scans were performed daily using the Hologic phantom. To minimize operator-related variability, all measurements were conducted by one of three experienced, certified technicians. Our error for BMC measurements is low, with a coefficient of variation of < 1% for quality control scans.

Structural geometry was determined from hip DXA images using the Hip Structure Analysis (HSA) program version 3.1. The program is based on a principle first described by Martin and Burr [21], that the mass in a pixel value calibrated in g/cm^2 of hydroxyapatite can be converted to linear thickness in cm by dividing by the effective mineral density of fully mineralized adult bone. Our specific methods have been described [3,4,13]. Briefly, a line of pixels traversing the bone axis provides a projection of the surface area of bone in the cross-section [4]. For the femoral neck (FN), the HSA program locates cross-sections traversing the femoral neck at its narrowest point. The (blur-corrected) subperiosteal bone width (cm), bone cross-sectional area (CSA in cm^2), and cross-sectional moment of inertia (CSMI in cm^4) for bending in the image plane were measured and Z (cm^3) was calculated from these values. In this report, CSA, an index of axial strength comparable to BMC, and Z, an index of bending strength, were used to describe structural properties of the FN. Note that because the HSA algorithm assumes a tissue mineralization of adult cortical bone, the CSA and Z will be systematically underestimated in the less mineralized bones of growing children [4,12]. Scan data were calibrated for the HSA program using a special phantom scanned at the University of Iowa and corrections specific to the Hologic scanners were incorporated into the analysis. HSA precision has not yet been assessed in children; however, experience in mainly elderly populations indicates that precision is 2.8% and 3.4% for CSA and Z, respectively [3]. To accommodate the change in scanners between the ages 8 and 11 measurements, we used a standardized bone mass test object (phantom) designed for cross-calibrations of the HSA program [26]. The object was scanned 5 times each on both scanners to generate the calibration for scanner differences associated with pixel mass. We also corrected for bone height using an estimate of bone height based on an attenuation derived measure of total soft tissue thickness. The bone height is assumed to be at ½ this thickness above the table and the pixel spacing along the fan beam is corrected accordingly. When geometry was calculated, the calibrations were implemented directly in the HSA program via a scanner serial number linked look-up table.

Accelerometry-Based Measures of Physical Activity

Parents and children were shown an Actigraph uniaxial accelerometer (model number 7164, Fort Walton Beach, FL) attached to a nylon belt. The parents were instructed to fasten the belt at their child's waist (on the mid-axillary line) to provide a specific measure of ambulatory, weight-bearing activity [35]. At ages 5 and 8, children were asked to wear the monitors all day during waking hours for four consecutive days, including one weekend day, during one of the autumn months (September through November). Because variability in activity increases as children age, at the age 11 measurement they were asked to wear the monitors all day during waking hours for five consecutive days, including both weekend days. Monitors and data

recording sheets were sent to parents and returned via prepaid U.S. mail. To be included in the data analyses, children had to wear the accelerometer at least eight hours per day for at least three days and within 15 months of the DXA scan.

The Actigraph accelerometer measures normal human movement using an internal piezoelectric cantilever beam that creates a charge proportional to the magnitude of movement [16]. In our study, movement count values were accumulated and summed over one-minute intervals. Studies examining this activity monitor and the construction of summary variables for intensity of movement indicate that it provides a valid and reliable measure of children's physical activity [7,8,15,16,33]. In this report, we used a summary variable of daily minutes spent in moderate and vigorous physical activity (MVPA). The variable was derived using the cut-point threshold of 3,000 accelerometry movement counts per minute ($ct.min^{-1}$). In laboratory-based studies of children, this cut-point (3,000 $ct.min^{-1}$) has been associated with normal walking speeds [33,34].

At each DXA visit, research nurses trained in anthropometry measured the child's height (cm) using a Harpenden stadiometer (Holtain, UK) and body mass (kg) using a Healthometer physician's scale (Continental, Bridgeview, IL). Both devices were routinely checked for accuracy and precision. Children were measured while wearing indoor clothes, but without shoes. Heights and weights were recorded to a precision of tenths of centimeters and tenths of kilograms, respectively.

Statistical Analysis

Gender-specific means and standard deviations were calculated to describe the distributional properties of the measures. Student's t-test was used to examine gender differences. Multilevel (random- and fixed-effects) regression models were constructed using PROC MIXED (SAS version 9.1.3) [31]. This approach allowed us to include children who missed one of the measurement periods. In the multilevel models, the slope and intercept for age (at the time of the DXA scan) were specified as random effects and PROC MIXED estimated their variance-covariance parameters [6]. Residual diagnostic plots were used to check the model assumptions and possible outliers. The models included centered age (8.5 yr), centered age^2 (to allow for non-linearity of growth), height, weight, time interval (between accelerometer and DXA measures), and MVPA as "time-varying" predictors that changed over the multiple assessments. Centering age at 8.5 yr (approximately the mean over the entire data set) allowed us to estimate the variance of a random intercept for age without extrapolating to chronological age 0 where there would be a large vertical spread in the extrapolated lines [2]. For all analyses, p-values < 0.05 were considered statistically significant and all statistical tests were two-tailed. In the multilevel regression models, MVPA was grouped in 10 minute intervals, rather than one minute intervals, in order to avoid very small coefficient estimates.

RESULTS

Description of Children

Table 1 presents a description of the children at the time of each examination (approximately 5, 8, and 11 years of age), including age, body size, MVPA levels, and FN structural measures (CSA and Z). Boys had significantly greater lean mass, CSA, and Z than did girls at all three time periods. They also engaged in more MVPA than did girls at all three examinations. At age 8, the boys were taller and weighed more than the girls. The average time of monitor wear per day was 747 minutes (SD 45 minutes). The range for daily accelerometry wear was 530 to 895 minutes. Ninety percent of the accelerometry measures were within 4.5 months of the DXA scan date.

Multilevel Regression Models for FN CSA and Z

Gender-specific hierarchical random effects models for FN CSA and Z are presented in Tables 2 and 3. The random-effects components of the models presented in Table 2 indicate that each child's CSA and Z is a function of his or her values at 8.5 yr (the centered age), his or her linear growth trajectory, plus his or her random error as it varied by age. The significant intercept variance ($p < 0.001$ for each model) indicates that children varied in their level of CSA and Z. The significant centered age (slope) variance ($p < 0.001$ for each model) indicates that they also varied in the rate of change in CSA and Z with increasing age. The fixed-effects component of the models presented in Table 2 indicate that for the entire group (sample mean), age, weight, height, and MVPA contributed to the explanation of CSA and Z. The time interval (between accelerometer and DXA measures) was also significant but did not influence the main effects. In addition, there was a significant positive centered age^2 association with CSA and Z for boys and girls ($p < 0.001$) in the fixed-effects component of the models. This finding supports the use of non-linear growth models. When the multilevel model is considered in its entirety, after controlling for growth and time between accelerometer and DXA measures, MVPA has a significant independent effect on CSA and Z for both boys and girls. For example, a boy, who on average, participated in 40 minutes of MVPA per day would be expected to have 0.056 cm^2 more CSA (3×0.0185) and 0.024 more Z (3×0.0079) than a boy who, on average, participated in 10 minutes of MVPA per day. At age 8, this is approximately a 4.0% difference in CSA and 5.0% difference in Z. For girls, the difference between 10 minutes and 40 minutes of MVPA per day was 0.043 for CSA (3×0.0143) and 0.014 for Z (3×0.0048). This is a difference of 3.0% at age 8 for CSA and Z. In general, 10 minute increases in daily MVPA had a similar effect on CSA for girls and a similar effect on Z for boys (slope) than a 1 kg increase in body weight. The effect of 10-minute increases in daily MVPA on CSA for boys was greater than a 1 kg body weight increase (0.0185 slope for MVPA versus 0.0131 slope for weight,). However, its effect was less than a 1 kg body weight increase on Z for girls (0.0048 slope for MVPA versus 0.0080 slope for weight).

Using this same approach, we examined the possible age-related increase in the effect of MVPA on CSA and Z by adding an interaction effect term for centered age and MVPA. These results, reported in Table 3, explore the likelihood that the same level of MVPA might have a greater or lesser impact on CSA and Z depending on the child's age. The interaction effect for centered age and MVPA was significant for CSA and Z for boys, but not for girls. This result suggests that as boys age, MVPA is associated with a greater increase in CSA and Z when compared to the same level of MVPA for the same boys when they were younger.

Table 4 presents models controlling for age, height, and total body lean mass (rather than weight). This analysis, tested the possibility that lean tissue (as a proxy of muscle force) mediated the influence of MVPA on CSA and Z. For boys, MVPA continued to have a significant independent effect on CSA and Z. However, the slope is smaller, suggesting that once the model is adjusted for the effect of lean mass, the effect of MVPA is reduced (though not eliminated). For girls, once the effects of age, height, and lean mass are controlled, MVPA is no longer a significant predictor of CSA or Z. Results (not shown) for boys and girls were similar when leg lean mass was substituted for total body lean mass.

DISCUSSION

In this study we examined longitudinal associations among children's everyday physical activity and FN structural measures of axial (CSA) and bending (Z) strength using multilevel (individual growth) modeling. The use of accelerometry technology to quantify physical activity and the use of HSA to estimate bone structural measures are novel components of this study. In addition, the statistical method of multilevel modeling provided a unique view of the relationship between children's physical activity and bone strength. The use of multilevel

models allowed us to circumvent several limitations of more commonly-used repeated measures techniques. For example, repeated-measures analysis of variance assumes that the overall pattern of change within the cohort generalizes to all children [6]. On the other hand, multilevel models allowed us to fit each child with his or her own growth trajectory and that was important given slope and intercept coefficients varied across children in our study. This strategy improved the model's fit. The effect of this approach was the identification of independent inter-group effects of MVPA on bone geometry measures (CSA and Z) while controlling for the effects of growth (age) and age-dependent covariates of body size (height, weight or lean mass) [2].

In our cohort, physically active boys and girls had a greater CSA and Z than their less active peers throughout middle- and late-childhood. This result suggests that the bone geometry in children adapts to mechanical loading conditions imposed by their *usual* physical activity level. Mechanical loads imposed on bone during intervention studies may not generalize to normal playground activity. The observational nature of this work in children is important since it includes the everyday context in which mechanical loading occurs and more accurately reflects the type and amount of physical activity in which children voluntarily choose to engage. Ultimately, effective public health recommendations will require information from both intervention and observational studies.

The influence of MVPA on CSA and Z was greater in boys than girls in our study. Throughout the six years of observation, boys, on average, were more active than girls and this difference increased as the children aged. Specifically, girls were, on average, 24% less active than boys at age 5 yr based on MVPA, 35% less active at age 8 yr, and 47% less active at age 11 yr. These differences were a result of boys increasing their MVPA levels between ages 5 and 11 while during the same time period, the girls decreased their MVPA levels. Assuming a potential causal association between physical activity and bone structural measures, greater levels of MVPA would be expected to result in greater CSA and Z. As a side note, at age 11 the children self-reported their levels of organized and unorganized leisure activities and sports. There was no statistically significant difference between boys and girls with respect to the number of organized activities in which the children participated, their participation time (organized or unorganized), and there were few differences between boys and girls with respect to types of activities that they reported (organized or unorganized). This suggests that diverging gender-related patterns of MVPA (as measured using accelerometry) may exist within similar patterns of leisure activity participation.

In our study, there was an interaction effect between age and MVPA for boys, but not for girls. We interpret this result to indicate that throughout middle- and late-childhood, the influence of physical activity on CSA and Z is similar for girls as they age; however, as boys age, physical activity has a greater influence on CSA and Z. This finding suggests the possibility of a "window of opportunity" just prior to adolescence for using exercise as an intervention to improve bone strength in boys. Recently, Macdonald and colleagues [19] reported concordant findings from the *Action Schools! BC Study* in British Columbia. After a 16-month jumping intervention, they showed targeted loading effective for increasing tibial bone strength in prepurbertal boys, but not early pubertal boys (mean age at baseline 10.3 yr for all boys). In *Healthy Bones*, another large school-based intervention in British Columbia, McKay and colleagues used HSA to show a greater apposition on the FN periosteal surface for peri-pubertal boys and a greater apposition on the FN endosteal surface for peri-pubertal girls [20,27]. This latter work suggests that as children enter puberty, differences in hip geometry, particularly Z, associated with physical activity are greater in boys than girls. These maturity- and sex-specific differences may be driven by increasing levels of sex steroids or some other (unknown) mechanism. The interaction effect between age and MVPA that we observed in boys may also be due to subtle differences in the magnitude, type, and variety of the physical activities that

the boys in our study selected as they aged, compared to the choices they made when they were younger.

The largest physiologic loads placed on bones are from muscle contractions. Since muscle forces scale with muscle size and lean mass is predominantly muscle, we examined whether physical activity predicted CSA and Z after controlling for total body lean mass [29]. Recent investigations have shown strong predictive relationships between lean mass and bone structure measures [9,20,25,26]. Our results suggest that lean mass may mediate the relationship between physical activity and FN bone structure measures in girls, but it does not fully explain the physical activity effect on these same measures in boys. This finding of a residual effect of physical activity after controlling for lean mass in boys is in contrast to a recent paper by the *Saskatchewan Paediatric Bone and Mineral Accrual Study* investigators [10]. The Saskatchewan investigators reported non-significant effects of physical activity on CSA and Z when total body lean mass or leg lean mass was included in regression models [10]. The difference between our study results and the Saskatchewan study results may be due to differences in subject ages since we studied children and the Saskatchewan cohort was primarily adolescents. Or perhaps our use of accelerometry technology, rather than questionnaires, provided a more precise and direct quantification of physical activity that allowed us to detect its residual effects. In an earlier cross-sectional analysis of our cohort at age 5, after controlling for lean mass, we found physical activity to be independently associated with CSA and Z in both boys and girls [13]. We did find that the effect of physical activity was reduced when compared to models that did not include lean mass, suggesting that most of the effect was mediated though greater muscle bulk. Since, on average, the boys in our cohort were more physically active than the girls and the gender-specific difference in physical activity levels increased with age, we speculate that a specific threshold or load of physical activity may be needed to detect its independent effect on FN bone structure parameters and that this amount of physical activity was not met by the girls in our study as they aged. Alternatively greater homogeneity in the activity level in girls may make a real effect more difficult to detect using these methods.

Our research has limitations. Though the cohort has been studied longitudinally, it is a convenience sample which suggests that subjects may not be representative of all U.S. children. Accelerometry as a measure of free-living physical activity is not error-free. For example, the accelerometry cut-point method that we used to determine MVPA was calibrated in laboratory settings [33,34]. Greater variability would be expected during free-living activity; therefore, our MVPA variable should be interpreted as indicating a relatively high intensity of movement ($\geq$ 3,000 movement counts.min^{-1}) rather than a precise metabolic or mechanical load. It is also likely that the one-minute time frame used to summarize our accelerometry movement count data missed shorter bouts of high-intensity physical activity [35]. On the other hand, our cut-point approach, one-minute time frame, accelerometer model, number of days measured, and number of hours measured per day are nearly identical those used in a recently published *Avon Longitudinal Study of Parents and Children* study [32]. In this work, Tobias and colleagues showed that accelerometry-measured MVPA was related to bone size and BMD in a very large cohort (n = 4,457) of 11-year-old children [32].

Other limitations of our study include potential differences in lean mass estimates between the Hologic 2000 DXA scanner that was used for age 5 and age 8 examinations and the Hologic 4500 DXA scanner that was used at the age 11 examination. In addition, we measured the left hip of all children but did not ascertain whether the left leg was non-dominant. Though the HSA program is commonly used in adults and more recently in children, there are limitations to its use [24]. In particular, bending strength indices are measured only in the plane of the scan image; bending strength differences in other directions may exist; however, they cannot be determined by our method [4]. In addition, the HSA algorithm assumes average

mineralization of 1.05 g/cm^3 which is appropriate for adults [3]. Lower mineralization densities would be expected in children and, therefore, a systematic underestimation of (absolute) CSA and Z is assumed [12]. Finally, maturational differences may have influenced our study results. We did not measure maturity throughout the six-year time span of the study. For most of our study period, it is logical to assume the children were not biologically mature. At the time of the age 11 examination, we estimated peak height velocity using the Mirwald method [22]. Sixteen percent of the girls, but none of the boys, had reached or were post peak height velocity. This was not surprising, since girls, on average, mature 2 yr earlier than boys; however, the level of maturity in girls may have confounded our results. However, our results indicated that the effect of MVPA on CSA and Z did not change as the girls aged.

In conclusion, when compared to less active peers, more physically active boys and girls have greater CSA (an index of axial strength) and Z (an index of bending strength) at the femoral neck. The strength of the positive association between physical activity and hip geometry is enhanced with age in boys. These results provide evidence that mechanical loading of the skeleton during childhood results in a positive effect on bone structural strength.

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Table 1

Description of the children at each examination.

Boys	**Age 5 (n=185)**		**Age 8 (n=212)**		**Age 11 (n=184)**	
	Mean	**(SD)**	**Mean**	**(SD)**	**Mean**	**(SD)**
Scan age, years	5.23	(0.44)	8.68	(0.60)	11.21	(0.31)
Time interval, months	4.92	(3.72)	4.85	(4.32)	3.48	(3.27)
Height, cm	112.05	(5.83)	134.47	(7.10)[a]	148.91	(7.45)
Weight, kg	20.43	(3.60	33.62	(10.01)[a]	45.00	(13.13)
Lean mass, kg	15.47	(2.12)[a]	23.36	(3.86)[a]	31.77	(6.14)[a]
MVPA, min.day^{-1}	31.66	(16.14)[a]	38.57	(21.26)[a]	41.63	(21.99)[a]
FN CSA, cm^2	0.94	(0.15)[a]	1.40	(0.24)[a]	2.33	(0.42)[a]
FN Z, cm^3	0.30	(0.07)[a]	0.52	(0.12)[a]	0.95	(0.24)[a]
Girls	**Age 5 (n=208)**		**Age 8 (n=233)**		**Age 11 (n=203)**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Scan age, years	5.30	(0.43)	8.72	(0.58)	11.21	(0.29)
Time interval, months	4.43	(3.12)	4.94	(3.94)	3.32	(2.71)
Height, cm	111.14	(5.59)	132.73	(6.71)[a]	148.90	(7.52)
Weight, kg	20.06	(3.84)	31.74	(8.47)[a]	43.62	(11.30)
Lean mass, kg	14.33	(1.88)[a]	20.99	(3.10)[a]	30.06	(5.77)[a]
MVPA, min.day^{-1}	24.21	(13.07)[a]	25.24	(13.46)[a]	22.13	(13.50)[a]
FN CSA, cm^2	0.87	(0.14)[a]	1.25	(0.20)[a]	2.17	(0.38)[a]
FN Z, cm^3	0.27	(0.06)[a]	0.45	(0.10)[a]	0.84	(0.19)[a]

Key: Time interval = absolute difference in months between DXA scan date and physical activity assessment (accelerometry) date. MVPA = moderate and vigorous physical activity (min.d^{-1}) ≥ 3,000 movement counts per minute

[a] $p < 0.05$ statistically significant difference between boys and girls in the same age group (Student's t-test).

Table 2

Gender-specific multilevel regression models for FN CSA and Z controlling for age, height, and weight and testing for the effect of MVPA.

	Boys				Girls			
	FN CSA Estimate	**SE**	**FN Z Estimate**	**SE**	**FN CSA Estimate**	**SE**	**FN Z Estimate**	**SE**
Random Variance-Covariance Estimates								
Intercept	0.0281	(0.0033)[a]	0.0064	(0.0008)[a]	0.0180	(0.0022)[a]	0.0035	(0.0004)[a]
Intercept with Centered Age	0.0061	(0.0007)[a]	0.0017	(0.0002)[a]	0.0041	(0.0005)[a]	0.0009	(0.0001)[a]
Centered Age	0.0010	(0.0002)[a]	0.0003	(0.0001)[a]	0.0007	(0.0002)[a]	0.0002	(0.0000)[a]
Residual	0.0140	(0.0015)[a]	0.0039	(0.0004)[a]	0.0129	(0.0013)[a]	0.0030	(0.0003)[a]
Fixed Effects								
Intercept	−0.4373	(0.2059)[c]	−0.3319	(0.0932)[a]	−0.8025	(0.1887)[a]	−0.4230	(0.0806)[a]
Centered Age	0.1411	(0.0093)[a]	0.0604	(0.0043)[a]	0.1066	(0.0087)[a]	0.0447	(0.0037)[a]
Centered Age^2	0.0344	(0.0012)[a]	0.0153	(0.0006)[a]	0.0360	(0.0011)[a]	0.0143	(0.0005)[a]
Height, cm	0.0098	(0.0017)[a]	0.0041	(0.0008)[a]	0.0115	(0.0016)[a]	0.0045	(0.0007)[a]
Weight, kg	0.0131	(0.0014)[a]	0.0080	(0.0007)[a]	0.0152	(0.0014)[a]	0.0080	(0.0006)[a]
Time Interval (per 30 d)	−0.0063	(0.0012)[a]	−0.0026	(0.0006)[a]	−0.0043	(0.0011)[a]	−0.0017	(0.0005)[b]
MVPA (for 10 min)	0.0185	(0.0034)[a]	0.0079	(0.0017)[a]	0.0143	(0.0042)[a]	0.0048	(0.0019)[c]

Key: Time interval = absolute difference per 30 days between DXA scan date and physical activity assessment (accelerometry) date. MVPA = moderate and vigorous physical activity (min.d^{-1}) ≥ 3,000 movement counts per minute.

[a] $p < 0.001$,

[b] $p < 0.01$,

[c] $p < 0.05$ in the gender-specific model.

Table 3

Gender-specific multilevel regression models for FN CSA and Z controlling for age, height, and weight and testing for MVPA and age interaction effect.

	Boys				Girls			
	FN CSA Estimate	**SE**	**FN Z Estimate**	**SE**	**FN CSA Estimate**	**SE**	**FN Z Estimate**	**SE**
Random Variance-Covariance Estimates								
Intercept	0.0274	(0.0032)[a]	0.0062	(0.0008)[a]	0.0180	(0.0022)[a]	0.0035	(0.0004)[a]
Intercept with Centered Age	0.0058	(0.0007)[a]	0.0016	(0.0002)[a]	0.0041	(0.0005)[a]	0.0009	(0.0001)[a]
Centered Age	0.0009	(0.0002)[a]	0.0003	(0.0001)[a]	0.0007	(0.0002)[a]	0.0002	(0.0000)[a]
Residual	0.0141	(0.0015)[a]	0.0040	(0.0004)[a]	0.0129	(0.0013)[a]	0.0030	(0.0003)[a]
Fixed Effects								
Intercept	−0.4546	(0.2077)[c]	−0.3401	(0.0939)[a]	−0.8022	(0.1887)[a]	−0.4233	(0.0807)[a]
Centered Age	0.1305	(0.0105)[a]	0.0535	(0.0049)[a]	0.1079	(0.0095)[a]	0.0448	(0.0041)[a]
Centered Age^2	0.0339	(0.0012)[a]	0.0150	(0.0006)[a]	0.0359	(0.0011)[a]	0.0143	(0.0005)[a]
Height, cm	0.0098	(0.0017)[a]	0.0040	(0.0008)[a]	0.0115	(0.0016)[a]	0.0045	(0.0007)[a]
Weight, kg	0.0133	(0.0014)[a]	0.0082	(0.0007)[a]	0.0152	(0.0014)[a]	0.0080	(0.0006)[a]
Time interval (per 30 d)	−0.0063	(0.0012)[a]	−0.0026	(0.0006)[a]	−0.0042	(0.0011)[a]	−0.0017	(0.0005)[b]
MVPA (for 10 min)	0.0215	(0.0037)[a]	0.0103	(0.0019)[a]	0.0135	(0.0048)[b]	0.0048	(0.0022)[c]
MVPA × Centered Age	0.0025	(0.0012)[c]	0.0017	(0.0006)[b]	−0.0006	(0.0017)	−0.0000	(0.0008)

Key: Time interval = absolute difference per 30 days between DXA scan date and physical activity assessment (accelerometry) date. MVPA = moderate and vigorous physical activity (min.d^{-1}) ≥ 3,000 movement counts per minute.

[a] $p < 0.001$,

[b] $p < 0.01$,

[c] $p < 0.05$ in the gender-specific model.

Table 4

Gender-specific multilevel regression models for FN CSA and Z controlling for age, height, and lean mass and testing for the effect of MVPA.

	Boys				Girls			
	FN CSA Estimate	**SE**	**FN Z Estimate**	**SE**	**FN CSA Estimate**	**SE**	**FN Z Estimate**	**SE**
Random Variance-Covariance Estimates								
Intercept	0.0231	(0.0027)[a]	0.0051	(0.0006)[a]	0.0162	(0.0018)[a]	0.0030	(0.0004)[a]
Intercept with Centered Age	0.0047	(0.0005)[a]	0.0012	(0.0001)[a]	0.0033	(0.0004)[a]	0.0007	(0.0001)[a]
Centered Age	0.0007	(0.0002)[a]	0.0002	(0.0000)[a]	0.0007	(0.0001)[a]	0.0002	(0.0000)[a]
Residual	0.0115	(0.0012)[a]	0.0031	(0.0003)[a]	0.0081	(0.0008)[a]	0.0020	(0.0002)[a]
Fixed Effects								
Intercept	−0.0048	(0.1981)	−0.1153	(0.0905)	−0.1929	(0.1793)	−0.1687	(0.0766)[c]
Centered Age	0.1122	(0.0090)[a]	0.0429	(0.0041)[a]	0.0822	(0.0081)[a]	0.0309	(0.0035)[a]
Centered Age^2	0.0274	(0.0013)[a]	0.0115	(0.0007)[a]	0.0264	(0.0012)[a]	0.0095	(0.0006)[a]
Height, cm	0.0019	(0.0018)	−0.0002	(0.0008)	0.0025	(0.0016)	0.0005	(0.0007)
Lean Mass, kg	0.0469	(0.0031)[a]	0.0275	(0.0016)[a]	0.0515	(0.0028)[a]	0.0258	(0.0013)[a]
Time Interval (per 30 d)	−0.0051	(0.0011)[a]	−0.0019	(0.0005)[a]	−0.0035	(0.0010)[a]	−0.0012	(0.0005)[b]
MVPA (for 10 min)	0.0119	(0.0032)[a]	0.0037	(0.0015)[c]	0.0066	(0.0037)	0.0008	(0.0017)

Key: Time interval = absolute difference per 30 days between DXA scan date and physical activity assessment (accelerometry) date. MVPA = moderate and vigorous physical activity (min.d^{-1}) ≥ 3,000 movement counts per minute.

[a] $p < 0.001$,

[b] $p < 0.01$,

[c] $p < 0.05$ in the gender-specific model.