JOURNAL OF BONE AND MINERAL RESEARCH
Volume 17, Number 3, 2002

A Randomized School-Based Jumping Intervention Confers Site and Maturity-Specific Benefits on Bone Structural Properties in Girls: A Hip Structural Analysis Study

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ABSTRACT

We compared 7-month changes in bone structural properties in pre- and early-pubertal girls randomized to exercise intervention (10-minute, 3 times per week, jumping program) or control groups. Girls were classified as prepubertal (PRE; Tanner breast stage 1; $n = 43$ for intervention [I] and $n = 25$ for control [C]) or early-pubertal (EARLY; Tanner stages 2 and 3; $n = 43$ for I and $n = 63$ for C). Mean ± SD age was 10.0 ± 0.6 and 10.5 ± 0.6 for the PRE and EARLY groups, respectively. Proximal femur scans were analyzed using a hip structural analysis (HSA) program to assess bone mineral density (BMD), subperiosteal width, and cross-sectional area and to estimate cortical thickness, endosteal diameter, and section modulus at the femoral neck (FN), intertrochanter (IT), and femoral shaft (FS) regions. There were no differences between intervention and control groups for baseline height, weight, calcium intake, or physical activity or for change over 7 months ($p > 0.05$). We used analysis of covariance (ANCOVA) to examine group differences in changes of bone structure, adjusting for baseline weight, height change, Tanner breast stage, and physical activity. There were no differences in change for bone structure in the PRE girls. The more mature girls (EARLY) in the intervention group showed significantly greater gains in FN (+2.6%, $p = 0.03$) and IT (+1.7%, $p = 0.02$) BMD. Underpinning these changes were increased bone cross-sectional area and reduced endosteal expansion. Changes in subperiosteal dimensions did not differ. Structural changes improved section modulus (bending strength) at the FN (+4.0%, $p = 0.04$), but not at the IT region. There were no differences at the primarily cortical FS. These data provide insight into geometric changes that underpin exercise-associated gain in bone strength in early-pubertal girls. (J Bone Miner Res 2002;17:363–372)

Key words: **bone mineral density, pediatric, exercise, bone structural properties, geometry**

INTRODUCTION

Our understanding of bone's response to mechanical loading in children and adolescents has been hampered by the inability of dual-energy X-ray absorptiometry (DXA) technologies to distinguish geometry from density and to assess the bone structural changes that underpin bone densitometric changes.[(1–3)] Growing bone can adapt to improve bone strength in response to increased mechanical loads by geometrically (re)modeling in a number of ways. First, bone can increase in *periosteal dimensions* through the apposition of new bone to the periosteal surface. These geometric changes confer a significant structural advantage because marginal subperiosteal expansion translates into consider-

The authors have no conflict of interest.

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able increases in cross-sectional moment of inertia (CSMI; CSMI is proportional to the fourth power of the radius). An increase in CSMI would result in increased *section modulus*. Section modulus as a measure of bone stiffness is closely related to the bending and torsional strength of bone. These structural parameters reflect the optimal redistribution of bone around the neutral axis and the cortical dimensions. Second, adaptation could occur as a result of diminished bone resorption from the *endocortical surface,* resulting in less medullary expansion. It has also been proposed that net endocortical apposition occurs during periods of accelerated growth in girls(4,5) and as a result of vigorous physical activity.(6) These processes would yield a smaller increase in endosteal diameter and an increased cortical width. An increase in the amount of bone within the periosteal envelope would also improve bone strength (represented by increased bone mineral content [BMC] determined by DXA or cross-sectional area [CSA] determined by the hip structural analysis [HSA]). As bone densitometric procedures are most commonly used to assess change in bone mass (BMC, g) or areal bone mineral density (aBMD, g/cm^2) following intervention, these structural parameters are infrequently reported.

Changes in bone shape or increases in bone size, which are often observed in response to mechanical loading in animals, would not necessarily translate into increased DXA measures of BMC or aBMD. However, geometric adaptations, which may occur more readily in children,(7) confer a considerable strength advantage that may be overlooked in traditional DXA studies. Alternatively, during growth, bone may adapt to loading by increasing aBMD without increasing section modulus; this occurred in one intervention study of prepubertal boys(8) and prepubertal female gymnasts.(9) Whereas several studies show increased BMC and aBMD with exercise intervention in growing children,(8,10–12) only one study has begun to address bone geometric adaptation in girls.(13) The ultimate goal of exercise interventions is to successfully induce a permanent change in bone geometry and thus bone strength. This, in turn, may have lifelong implications with respect fracture risk.(7)

We have recently demonstrated the maturity-specific time during early childhood when exercise is most effective for enhancing bone mineral accrual.(14) For this study, we also assessed change in bone structural properties in this pre- and early-pubertal group using the HSA program.(15) The purpose of the present study, therefore, was to examine the geometric and structural adaptations of bone with exercise intervention specific to pre- and early-puberty. We addressed the following questions. 1) Is there a geometric bone response to exercise intervention in prepubertal girls? 2) What are the geometric adaptations underlying the increased BMC/aBMD in early-pubertal girls? 3) Do those changes translate to an increase in bone strength as represented by section modulus? 4) What are the regional differences in structural adaptation within the proximal femur? Based on the literature and our earlier findings(14) we hypothesized the following: 1) early-pubertal girls in the exercise group would have a greater increase in section modulus compared with controls; 2) greater subperiosteal expansion would underpin this adaptation; and 3) structural adaptations to the exercise intervention would be specific to the femoral neck region of the proximal femur.

MATERIALS AND METHODS

Design and participants

Schools were recruited in Richmond, British Columbia, a suburb of Vancouver, Canada, with a multi-ethnic population including ~34% Hong Kong Chinese and 57% white. Fourteen schools volunteered for the study, and a total of 383 students from grades 4, 5, and 6 (ages 9–12 years), participated. Schools were stratified by ethnic composition and randomly assigned to either control or intervention groups.(14) The protocol was approved by the ethical review boards for the University of British Columbia and the Richmond School District. Parents and children signed informed consent before participation. Methods of this study have been detailed elsewhere.(14) In this analysis, we investigated 177 girls classified as either pre- or early-pubertal based on Tanner breast stage.

Maturity

Pubertal stage was classified by self-assessment of Tanner breast stage using a standard approach(16) previously used in this age group.(10,17) Self-assessment of maturity is strongly correlated with staging assigned by an endocrinologist(18,19) and is practical to use with children in a school-based setting. Girls were classified as prepubertal (PRE) if they were Tanner stage 1 at baseline ($n = 70$; 26 control, 44 intervention) and early-pubertal (EARLY) if they were Tanner stages 2 or 3 at baseline ($n = 107$, 64 control, 43 intervention).

Anthropometry

Stretch stature (without shoes) and sitting height was recorded to the nearest 0.1 cm using a stadiometer. Weight was measured on an electronic scale to the nearest 0.1 kg.(14)

Calcium and physical activity

A food frequency questionnaire (FFQ) was used to estimate dietary calcium intake. The questionnaire has been validated in Asian and white adolescents living in Vancouver.(20)

General physical activity was determined using a modified version of the Physical Activity Questionnaire for Children (PAQ-C),(21) which assesses daily activity over the past 7 days and is scored from 1 (low activity) to 5 (high activity). The questionnaire also included questions regarding loading activity (impact > walking) and an indication of the number of nights per week the child participated in organized sports (sport nights). Thus, three physical activity variables were calculated: average physical activity (score from 1–5), load time (hours per week of weight-bearing activity), and sport nights (days per week of organized sports). Both questionnaires were administered three times

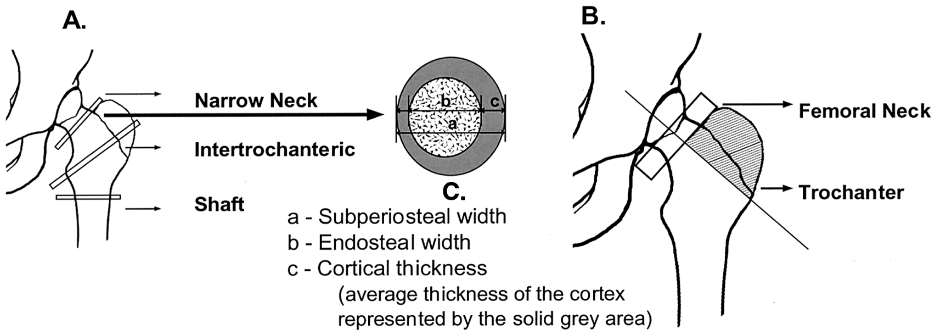


FIG. 1. Proximal femur schematic showing (A) positions of HSA regions across the femur at the narrow neck, intertrochanteric region, and femoral shaft region compared with (B) standard DXA regions. (C) A schematic of the cross-sectional geometric variables calculated from the HSA program that are described in detail in the text.

over the year and have been used extensively in previously published studies in similar aged children.[10,17,22,23]

Bone densitometry

Left proximal femur scans were acquired on a Hologic Inc. QDR-4500 bone densitometer (Hologic Inc., Waltham, MA, USA) in array mode. Assessments were made at baseline and after 7 months of intervention by the same two qualified researchers (K.M. and M.P.). Standardized positioning protocol[24] was used, and the system phantom was scanned daily to maintain quality control. Coefficients of variation for BMD (g/cm^2) in our laboratory ranged from 0.5% to 1.2% in 10 adults scanned three times with repositioning.

HSA

Proximal femur scans were analyzed for structural characteristics using the HSA program designed by Dr. Tom Beck at Johns Hopkins University (Baltimore, MD, USA). This method has been described in detail elsewhere[1,15,25,26] and has been used in large adult and aging populations.[27–29] Three narrow regions were analyzed corresponding to thin cross-sectional slabs of 5-mm-thick bone. Regions assessed (Fig. 1A) were as follows: 1) the *narrow neck*—across the narrowest segment of the femoral neck, 2) the *intertrochanteric* region along the bisector of the neck-shaft angle, and 3) the *shaft*, 2 cm distal to the midpoint of the lesser trochanter. For each region the distribution of the bone mass across the bone was extracted and the subperiosteal width (cm), bone cross-sectional area exclusive of soft-tissue spaces (CSA, cm^2), and cross-sectional moment of inertia (CSMI, cm^4) were measured directly from the bone mass profile. In addition, estimates of cortical thickness were obtained with simple models of the cross-sections that employ measured dimensions and assumptions of cross-section shape. Section modulus (Z), an indicator of bone bending strength, was calculated ($Z = CSMI/y$), where $y = 1/2$ subperiosteal width for the neck and shaft regions and the distance from the centroid to the lateral cortical margin for the intertrochanteric region. Collectively, we refer to these variables as "bone structural variables" in this report. BMD (g/cm^2) is calculated in the conventional manner, although these regions of interest do not have counterparts in the standard Hologic BMD analysis (Fig. 1B). Therefore, absolute BMD values may differ.[15,25] Variables are shown in Fig. 1C.

Longitudinal data were analyzed using the pediatric program that permits enlarging of the template to allow for growth. One individual analyzed all scans within a 72-h period. To assess intraoperator precision for scan analysis, the same individual analyzed 10 randomly selected scans three times. Coefficients of variation for analysis ranged from less than 0.1% to 1.2%. Data were checked closely for positioning errors and three control participants (2 PRE and 1 EARLY) were excluded from the intertrochanteric analysis due to implausible change values.

Exercise intervention

The exercise intervention was designed to provide a brief (10–12 minutes), high impact session during regularly scheduled physical education classes two times per week and on one additional day in the classroom. Children rotated through five stations and performed diverse jumping exercises. The intervention was progressive over the school year, and we increased both the number of jumps (from 10 to 20 jumps) and the height (from 10 to 50 cm) for increased intensity of the activity. Students progressed through three levels that lasted 3 months each. Students jumped a minimum of 50 times at each initial session and progressed to 100 jumps by the end of each level. Ground reaction forces for a subset ($n = 70$) of participants averaged 3.5–5.0 times body weight for the various circuit exercises.[30] The circuit training program has been described in detail elsewhere.[14,31]

Statistical analyses

Descriptive statistics presented include means, SDs (for baseline), and 95% CIs (for change). As the relationship between covariates and change in bone structural variables differed between maturity groups, separate analyses were used to compare exercise and control groups within each maturity group (PRE or EARLY). Independent *t*-tests were used to compare baseline values for all variables. Analysis of covariance (ANCOVA) was used to determine group differences in change variables.

Covariates were selected based on the theoretical and actual relationship to change in bone structural variables. Several factors may potentially influence change in bone

TABLE 1. BASELINE DESCRIPTIVE VARIABLES FOR PRE- (TANNER BREAST STAGE 1) AND EARLY- (TANNER BREAST STAGES 2 AND 3) PUBERTAL GIRLS IN CONTROL AND INTERVENTION GROUPS (MEAN ± SD)

	Prepubertal		*Early-pubertal*	
	Control	*Intervention*	*Control*	*Intervention*
N	26	44	64	43
Age (years)	10.1 ± 0.5	10.0 ± 0.6	10.5 ± 0.6	10.4 ± 0.7
Height (cm)	137.3 ± 6.2	138.6 ± 7.6	145.6 ± 6.4	143.8 ± 7.7
Sitting height (cm)	72.5 ± 3.2	73.3 ± 3.4	77.1 ± 3.5	76.0 ± 4.5
Leg length (cm)	64.8 ± 3.8	65.5 ± 4.6	68.6 ± 3.6	67.6 ± 4.2
Weight (kg)	31.5 ± 5.6	31.2 ± 6.1	41.3 ± 8.3	39.1 ± 8.3
Lean mass (g)	22,455 ± 3,022	22,943 ± 3,160	27,802 ± 3,980	26,588 ± 4,478
Fat mass (g)	7,566 ± 2,916	7,289 ± 3,432	12,046 ± 5,341	11,107 ± 4,667

structure. These include the following: 1) body/bone size at baseline (i.e., baseline bone, height, weight), 2) rate of linear growth (change in height or weight), 3) maturity or age (Tanner breast stage or age), and 4) physical activity (physical activity score, load time, or sport nights). We selected one variable that represented size at baseline (baseline weight), one variable that reflected change in size over the treatment period (height change), one maturity variable (Tanner breast stage—baseline for PRE and final for EARLY), and one physical activity variable (sport nights) for covariates based on the strength of their relationship to the dependent variable in multiple regression. Covariates that consistently entered into stepwise models as significant predictors of change in hip structural variables were baseline weight, height change, Tanner breast stage, and sport nights.

RESULTS

Descriptive variables for PRE and EARLY groups are summarized in Table 1. Within each maturity category, the intervention and control groups were well matched at baseline. There were no significant differences between the groups for height, weight, fat or lean mass, calcium intake, or average physical activity. Change in height and weight did not differ between the intervention (I) and control (C) groups within each maturity category (all $p > 0.10$) as previously reported.[14] Seven-month change in total body lean mass (PRE: C = 1807 ± 920 g, I = 1807 ± 931 g; EARLY: C = 2925 ± 968 g, I = 2786 ± 1247 g) and fat mass (PRE: C = 533 ± 728 g, I = 397 ± 993 g; EARLY: C = 1038 ± 1554 g, I = 616 ± 1624 g) were also not different between groups (all $p > 0.10$).

In the PRE girls, 62% of the control group and 41% of the intervention group advanced to Tanner stage 2. A similar number of EARLY girls in control (22%) and intervention (14%) groups were both Tanner stage 3 at baseline and advanced at the same rate during the study. The ethnic distribution in the intervention and control groups was also similar (~50% white, 30% Asian, and 20% "other" or mixed ethnicities).

Changes due to growth and development

All bone structural variables increased significantly over 7 months ($p < 0.01$), except for the femoral shaft endosteal diameter that did not change significantly from baseline in either PRE or EARLY girls (Table 2). Endosteal expansion occurred in the femoral neck and intertrochanteric regions (3–5%). Section modulus increased at all regions (10–18%) largely due to periosteal apposition (3–5%) and increased cortical thickness (3–9%). There were no discernible differences in the pattern of bone growth and development between maturity groups. aBMD also increased significantly at all sites (3–8%).

Changes due to exercise intervention

Within the PRE girls, there were no significant differences for change in any bone structural variable between intervention and control groups at any site (Table 2). As we previously reported for conventional DXA evaluations,[14] change in BMC and aBMD also did not differ between exercise and controls in the PRE group at any site (including total body, lumbar spine, and total proximal femur).

After controlling for covariates, the more mature girls (EARLY) in the intervention group showed significantly greater gains in femoral neck (+2.6%, $p = 0.027$) and intertrochanteric (+1.7%, $p = 0.016$) aBMD than controls. Underpinning these changes at the femoral neck (Fig. 2) were increased bone cross-sectional area (+2.3%, $p = 0.040$) and increased cortical thickness (+3.2%, $p = 0.032$). The increased cortical thickness resulted from lesser endosteal expansion in the exercise group (−1.0%, not significant). Similarly, at the intertrochanteric region, the intervention group had lesser endosteal expansion than controls (−1.4%, $p = 0.015$). Changes in subperiosteal width did not differ significantly at any site, although there was an apparent trend toward lower values in the intervention group at the femoral neck and intertrochanteric sites (Table 2). Structural changes led to a greater increase in section modulus (a surrogate for bending strength) at the femoral neck (+4.0%, $p = 0.034$) but not the intertrochanteric region. Structural changes (%) at the femoral neck are illustrated in Fig. 2. There were no differences for change in any variable at the femoral shaft.

TABLE 2. STRUCTURAL PROPERTIES FOR INTERVENTION VERSUS CONTROL GROUPS FOR PREPUBERTAL GIRLS (TANNER STAGE 1). BASELINE, MEANS ± SD; CHANGE, ADJUSTED MEANS (95% CI)

	Baseline		*Change**	
	Control	*Intervention*	*Control*	*Intervention*
N	26	44	26	44
Narrow Neck				
Neck length (cm)	3.73 ± 0.442	3.72 ± 0.469	0.420 (0.282–0.559)	0.300 (0.201–0.400)
BMD (g/cm^2)	0.874 ± 0.099	0.857 ± 0.112	0.027 (0.011–0.043)	0.022 (0.011–0.033)
CSA (cm^2)	2.00 ± 0.278	1.97 ± 0.282	0.147 (0.114–0.181)	0.126 (0.102–0.151)
Subperiosteal width (cm)	2.40 ± 0.171	2.42 ± 0.257	0.106 (0.061–0.150)	0.095 (0.063–0.127)
Section modulus (cm^3)	0.788 ± 0.140	0.781 ± 0.159	0.080 (0.058–0.102)	0.072 (0.056–0.088)
Estimated endosteal diameter (cm)	2.05 ± 0.174	2.09 ± 0.276	0.095 (0.046–0.145)	0.087 (0.051–0.122)
Estimated mean cortical thickness (cm)	0.172 ± 0.021	0.168 ± 0.024	0.005 (0.002–0.009)	0.004 (0.002–0.007)
Interochanter				
BMD (g/cm^2)	0.851 ± 0.108	0.826 ± 0.126	0.042 (0.030–0.054)	0.038 (0.029–0.046)
CSA (cm^2)	3.12 ± 0.454	3.03 ± 0.501	0.300 (0.253–0.346)	0.295 (0.261–0.328)
Subperiosteal width (cm)	3.85 ± 0.276	3.86 ± 0.341	0.170 (0.136–0.204)	0.191 (0.167–0.216)
Section modulus (cm^3)	1.91 ± 0.364	1.85 ± 0.441	0.293 (0.246–0.340)	0.320 (0.286–0.353)
Estimated endosteal diameter (cm)	3.14 ± 0.278	3.18 ± 0.363	0.124 (0.088–0.160)	0.146 (0.120–0.171)
Femoral Shaft				
BMD (g/cm^2)	1.10 ± 0.154	1.09 ± 0.134	0.074 (0.060–0.089)	0.065 (0.055–0.076)
CSA (cm^2)	2.28 ± 0.333	2.26 ± 0.328	0.230 (0.199–0.261)	0.207 (0.185–0.229)
Subperiosteal width (cm)	2.17 ± 0.152	2.18 ± 0.198	0.066 (0.051–0.081)	0.063 (0.053–0.074)
Section modulus (cm^3)	0.960 ± 0.179	0.964 ± 0.199	0.119 (0.102–0.136)	0.110 (0.098–0.123)
Estimated endosteal diameter	1.34 ± 0.251	1.37 ± 0.27	0.003 (−0.024–0.026)	0.006 (−0.012–0.024)
Estimated mean cortical thickness (cm)	0.42 ± 0.083	0.41 ± 0.069	0.033 (0.025–0.041)	0.029 (0.023–0.035)

* Covariates: baseline weight, height change, Tanner breast stage (time 2), and physical activity (sport nights).
All $p > 0.30$ for group differences.
Two control subjects excluded from analyses of intertrochanteric data.

DISCUSSION

This is the first study to prospectively investigate the role of mechanical loading on bone accrual and bone structural properties in premenarcheal girls at different pubertal stages (Tanner stage 1 vs. Tanner stages 2 and 3). Our data indicate that maturity- and site-specific changes in bone structural variables result from a school-based jumping intervention. This study shows that bone structure is not altered by intervention in prepubertal girls but adapts in response to exercise intervention in early-pubertal girls.

Structural adaptations to exercise intervention in prepubertal girls

Our current investigations did not reveal any differences in change in bone structural properties with exercise in the prepubertal group. These findings complement our previous work that reported increased gains in aBMD and BMC by DXA at the femoral neck in early-pubertal but not prepubertal girls.[14]

Structural adaptations underlying the increased BMC/aBMD in early-pubertal girls

In the early-pubertal exercise group there was a greater increase in bone cross-sectional area and section modulus at the femoral neck, which translated to significant gains in bone strength. At both the femoral neck and intertrochanteric regions, early-pubertal girls in the exercise group had relatively greater increases in aBMD and bone cross-sectional area (equivalent to BMC by conventional DXA), but not in subperiosteal dimensions. Thus, the greater increase in cross-sectional area at both sites arose because of less endosteal expansion (or diminished endosteal resorption) as well as an increase in bone within the periosteal envelope in the exercise group (Fig. 2). The greater increase in cortical thickness also reflects diminished resorption on the endosteal surface.

Periosteal and endosteal surfaces

We did not observe significantly greater periosteal apposition in the exercise group. This contrasts with a number of

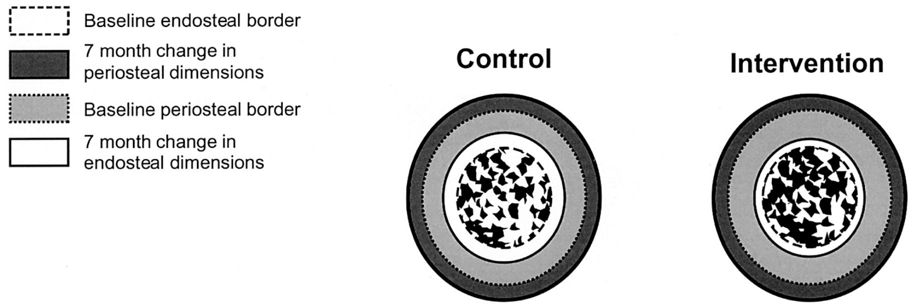
TABLE 3. STRUCTURAL PROPERTIES FOR INTERVENTION VERSUS CONTROL GROUPS FOR EARL-PUBERTAL GIRLS (TANNER STAGE 2 AND 3). BASELINE, MEAN ± SD; CHANGE, ADJUSTED MEANS (95% CI)

	Baseline		*Change*†	
	Control	*Intervention*	*Control*	*Intervention*
N	64	43	64	43
Narrow Neck				
Neck length (cm)	4.00 ± 0.474	3.89 ± 0.489	0.254 (0.161–0.346)	0.263 (0.152–0.374)
BMD (g/cm^2)	0.934 ± 0.140	0.922 ± 0.140	0.035 (0.021–0.049)	0.060 (0.043–0.077*)
CSA (cm^2)	2.30 ± 0.393	2.22 ± 0.378	0.198 (0.166–0.231)	0.252 (0.213–0.291*)
Subperiosteal width (cm)	2.57 ± 0.159	2.54 ± 0.248	0.132 (0.096–0.168)	0.104 (0.061–0.147)
Section modulus (cm^3)	0.960 ± 0.209	0.903 ± 0.193	0.106 (0.084–0.129)	0.145 (0.118–0.172*)
Estimated endosteal diameter (cm)	2.20 ± 0.162	2.17 ± 0.264	0.118 (0.078–0.158)	0.080 (0.032–0.128)
Estimated mean cortical thickness (cm)	0.184 ± 0.030	0.181 ± 0.030	0.007 (0.004–0.010)	0.012 (0.008–0.016*)
Intertrochanter				
BMD (g/cm^2)	0.903 ± 0.145	0.885 ± 0.127	0.053 (0.045–0.061)	0.069 (0.059–0.079*)
CSA (cm^2)	3.60 ± 0.715	3.50 ± 0.584	0.382 (0.346–0.418)	0.425 (0.382–0.468)
Subperiosteal width (cm)	4.18 ± 0.334	4.16 ± 0.387	0.194 (0.171–0.217)	0.159 (0.131–0.186)
Section modulus (cm^3)	2.47 ± 0.686	2.38 ± 0.575	0.424 (0.385–0.462)	0.447 (0.401–0.493)
Estimated endosteal diameter (cm)	3.43 ± 0.316	3.42 ± 0.377	0.138 (0.114–0.161)	0.092 (0.064–0.120*)
Femoral Shaft				
BMD (g/cm^2)	1.20 ± 0.184	1.18 ± 0.140	0.089 (0.077–0.100)	0.094 (0.080–0.108)
CSA (cm^2)	2.71 ± 0.502	2.62 ± 0.444	0.291 (0.262–0.319)	0.298 (0.265–0.332)
Subperiostal width (cm)	2.36 ± 0.209	2.31 ± 0.186	0.077 (0.064–0.090)	0.073 (0.057–0.088)
Section modulus (cm^3)	1.25 ± 0.297	1.17 ± 0.283	0.153 (0.137–0.170)	0.157 (0.138–0.177)
Estimated endosteal diameter (cm)	1.45 ± 0.300	1.42 ± 0.200	−0.008 (−0.030–0.014)	−0.014 (−0.041–0.012)
Estimated mean cortical thickness (cm)	0.458 ± 0.103	0.446 ± 0.065	0.042 (0.035–0.050)	0.043 (0.035–0.052)

† Covariates: baseline weight, height change, baseline Tanner breast stage, and physical activity (sport nights).
$p > 0.20$ for group comparison at baseline and $p > 0.54$ for all change variables at the femoral shaft.
* Significantly greater change than control group ($p < 0.05$).
One control subject excluded from analyses of intertrochanteric data.

animal studies that showed periosteal expansion with increased mechanical loading.[32–36] Studies have clearly demonstrated in adult animals that modeling activity increases farthest from the neutral axis—at the periosteal surface.[1,33] However, several of the studies that demonstrated this response intervened primarily with running activities in mature animals, which might partially explain the observed discrepancy between these outcomes and our study of immature bone. Those experiments also included surgical loading models that required instrumentation and immobilization. With that model, one study showed a 48% greater response on the periosteal surface compared with loading that was imposed in conjunction with everyday activities[37] in a natural environment. It may not be appropriate to generalize these loading models to human exercise interventions [37–40]

The few studies in humans that have assessed surface-specific effects of exercise show increased bone size and periosteal apposition in racquet sport players who began training during adolescence.[41,42] Tennis loads the humerus with high bending and torsional strains. Jumping activities also induce bending together with a larger component of axial compressive strains in the lower limb. A wider bone is more suited to resisting bending and torsional loads, whereas a bone with a greater bone surface in the CSA is better suited for compressive loads.[1,43] Bending or torsional strength could be improved by increasing the bone diameter; this would increase the section modulus, but unless the amount of bone within the subperiosteal envelope (CSA) were also increased, this would produce a *reduction* in aBMD. The jumping intervention used in this study should considerably increase the axial compression forces compared with that induced in most normal activity. Because axial compression is uniformly distributed through the cross-section rather than concentrated on the periosteal surface as in bending or torsion, it may be more likely to induce bone formation on the endosteal surface. This may be the reason that studies of activity effects on bone with aBMD as the endpoint show greater efficacy when impact forces are included. This view is supported by a recent study in young roosters that demonstrated increased bone formation activity on the endosteal surface in response to a drop



Variable	Control (% increase)	Intervention (% increase)
aBMD	3.7	6.6*
CSA	8.9	11.1*
Cortical Thickness	3.7	6.9*
Subperiosteal width	5.2	4.3
Endosteal diameter	5.4	4.0
Section modulus	11.7	15.7*

*significantly different from controls (p<0.05)

FIG. 2. Schematic representation (not to scale) of the geometric and mass changes (%) over 7 months in early-pubertal (Tanner breast stages 2 and 3) control (n = 64) and intervention (n = 43) girls at the narrow neck region on the proximal femur. Values are controlled for baseline weight, baseline Tanner breast stage, height change, and physical activity (sport nights). *$p < 0.05$ for between group differences.

jumping intervention. These animals had a +370% increase in endocortical bone formation compared with controls but only +40% increase in periosteal formation.[44] Although these high magnitude landings increased periosteal formation in the roosters, the response was significantly larger on the endocortical surface.

Overall in our study, endosteal expansion occurred in the growing hips of both exercise and control groups; however, expansion was reduced in the exercise group at both the femoral neck and the intertrochanteric regions, illustrated by smaller increases in estimated endosteal diameters. The HSA cannot show us whether bone resorption decreased, bone formation increased, or both. A study of prepubertal boys has previously reported significant increases in endosteal apposition with a moderate loading intervention that included activities likely to increase impact or axial loading.[8]

Changes translate to an increase in bone strength as represented by section modulus

In the early pubertal girls, the combined effect of a 4.3% increase in subperiosteal width and a 6.9% increase in cortical thickness translated into a 15.7% increase in section modulus at the femoral neck. This is compared with an 11.7% increase at the femoral neck observed in control girls. This illustrates how small increases in the radius of a bone's cross-section disproportionately influences the moment of inertia and therefore bone stiffness and strength.[45] The section modulus provides a measure of bone's intrinsic stiffness in bending or torsion and is closely related to the cross-sectional geometry.[1] The ability of bones to resist fracture when loaded is also closely related to material properties as well as geometry.[1,45] Thus, the greater concomitant increase in CSA at the femoral neck in the exercising girls provided a further strength advantage.

Regional differences in structural adaptation within the proximal femur

It is clear that long bone adaptation to mechanical loading is site-specific, but this is logical because the magnitudes, directions, and types of load vary along its length. Undoubtedly the loading characteristics vary considerably along the proximal end of the femur where measurements were made in this study. We observed site-specific structural changes in a subset of 18 prepubertal girls from this study who were assessed by magnetic resonance imaging (MRI). Periosteal expansion of the tibia over 7 months varied from 13% proximally to 21% distally.[46] This compares with the observation by Mosley et al.[33] of increased periosteal apposition in the loaded rat ulna at the distal end whereas mineral apposition rate was reduced toward the proximal end. Further, muscle mass was associated with tibial cortical bone area in the lateral cortex but not the posterior or anteromedial cortices.[47]

Animal studies also show that adaptation within a single bone cross-section varies in the medial-lateral and anterior-posterior direction and is dependent on the magnitude, type of strain, and location along the length of the bone.[33,44] The different adaptive responses we observed at the femoral neck, intertrochanteric region, and femoral shaft region emphasizes the site-specificity of the bone adaptive response.

Differences between intervention and control groups were observed at the predominantly cancellous bone sites of the femoral neck and intertrochanteric regions. The femoral shaft changed similarly in exercise and control groups. This could be due to the presence of primarily cortical bone at that site, the bending moments experienced at the distal femur in response to the type of loading, and/or the measurement location along the femur. In an exercise intervention study that assessed premenarcheal girls, there was no difference in change over 10 months between exercise and control girls in the largely cortical proximal tibia. However, significantly greater changes were noted at the femoral neck in the exercising group.[13] Both cortical and cancellous bone adapts to mechanical loading in animal studies.[48] It is not clear if the time-course for adaptation[49] or modeling thresholds differ between the two types of bone. A greater strain magnitude, rate, or duration of intervention may be necessary for an osteogenic response at the primarily cortical shaft of the femur and tibia.

In contrast to our study, Bradney et al.[8] showed increases in cortical thickness and decreased endocortical diameter (both changed ~1%/month) with intervention in prepubertal boys and the mid-shaft of the femur (from total body scans). Our methodological approach to assessing the femur was markedly different. The HSA program measures the femoral shaft (from proximal femur scans) 2 cm distal to the lesser trochanter (Fig. 1A)—a relatively proximal location. Several studies show a greater response to loading in the more distal portion of long bones.[43,48,50] In growing animals, loading induced periosteal bone formation only on the distal portion of rat ulnas.[50] In tennis players side-side differences in a number of parameters, including cortical bone area, cortical wall thickness, and bone strength index were significantly (15–20%) greater in the distal compared with the proximal humerus.[43] Clearly bone adaptation to mechanical loading is extremely site-specific and assessing only one region of long-bones does not necessarily represent the entire bone response.[1]

Methodological considerations

The results of this study illustrate the urgent need to assess change in bone geometry and structure rather than DXA measures of BMC and aBMD alone.[2,51] We demonstrated that bone can increase in mass without a concomitant increase in strength (e.g., at the intertochanteric region) and others have shown that the reverse is also true.[52,53] DXA is widely available and used in both pediatric and adult populations and provides important information and has many advantages. The HSA program provides a useful means of assessing bone structural parameters with DXA technology, but one must recognize that the technology is neither designed nor optimized for the measurement of geometry. There are clearly limitations in attempting to assess a three-dimensional structure using two-dimensional imaging techniques—particularly in growing children.[54,55] The HSA program extracts measurements of mass and dimensions from a two-dimensional image. If the subject position for scanning and the position of analysis regions on the scan image are not accurately reproduced in serial measurements, a systematic error in projected dimensions and thus in the derived geometry can occur. The estimates of cortical thickness and endosteal diameter employ assumptions of cross-sectional shape and in the relative distribution of trabecular and cortical bone within the neck and intertrochanteric cross-sections. These assumptions may not be completely realistic and their validity in children have not been assessed.

Despite these limitations, these sources of error should mainly degrade the sensitivity of the method in detecting subtle changes over time but not whether or not these changes in mass distribution and dimensions are occurring. Newer imaging modalities such as peripheral quantitative computerized tomography (pQCT) and MRI that can assess both bone and muscle in cross-sections have great potential for research.[47,51] Nevertheless all of these techniques are limited in some aspect, and future studies may need to combine several modalities to allow more comprehensive understanding of bone's adaptation to interventions.

We have shown that an exercise program that can be easily implemented into elementary school physical education programs[14,31] not only increases aBMD and BMC[14] but also improves bone structure and strength in early-pubertal girls. Bone adaptation to mechanical loading is not homogeneous but depends on the skeletal site, the specific structural variable of interest and the maturity of the participants.

ACKNOWLEDGMENTS

We thank the Richmond School District's teachers, parents, and children for their support and participation in this research. We thank Garry Tsang, M.Sc., for diligent scan analysis (HSA) and Tammy Orsovic for training on the HSA program. This study was supported by grants from BC Health Research Foundation (2400-2 and 10898-2).

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Received in original form May 27, 2001; in revised form August 20, 2001; accepted October 11, 2001.