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Initial Years of Recreational Artistic Gymnastics Training Improves Lumbar Spine Bone Mineral Accrual in 4- to 8-Year-Old Females

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ABSTRACT: Gymnasts' bone mineral characteristics are generally not known before starting their sport. Prepubertal females who enrolled in beginning artistic gymnastics (*n* = 65) had lower bone mineral than controls (*n* = 78). However, 2 years of gymnastics participation versus no participation led to a significantly greater accrual of forearm bone area and lumbar spine areal BMD.

Introduction: The skeletal response to exercise in children compared with adults is heightened because of the high bone turnover rate and the ability of bone to change its size and shape. Whereas child gymnasts generally have greater rates of bone mineral accrual compared with nongymnasts, it is unknown if some of these skeletal advantages are present before the onset of training or are caused entirely by training.

Materials and Methods: Changes in bone area (BA; cm^2), BMC (g), and areal BMD (aBMD; g/cm^2) over 24 months were examined in prepubertal females, 4–8 years of age, who selected to perform recreational gymnastics (GYM; $n = 65$), nongymnastic activities, or no organized activity (CON; $n = 78$). Participants had essentially no lifetime history of organized athletic participation (<12 weeks). Pubertal maturation was assessed annually by a physician. Total body, lumbar spine, total proximal femur, and forearm BA, BMC, and aBMD were measured every 6 months using DXA (Hologic QDR-1000W). Independent samples *t*-tests determined baseline group differences. Nonlinear mixed effects models were used to model 24-month changes in bone data. In subset analyses, high-level gymnasts advancing to competition (HLG; $n = 9$) were compared with low-level nonadvancing gymnasts (LLG; $n = 56$).

Results: At baseline, GYM were shorter, lighter, and had lower BA, BMC, and aBMD compared with CON ($p < 0.05$), whereas HLG did not differ significantly in these measurements compared with LLG ($p > 0.05$). Controlling for differences in race, baseline measures of body mass, height, and calcium intake, and change in breast development beyond stage II at 24 months, GYM had greater long-term (asymptotic) mean responses for total body aBMD and forearm BMC ($p < 0.04$) and greater rates of increase in the mean responses of lumbar spine aBMD and forearm BA compared with CON over 24 months. Over time, forearm BA increased to a greater extent in HLG compared with LLG ($p < 0.01$).

Conclusions: Females participating in recreational gymnastics initiated during childhood have enhanced bone mineral gains at the total body, lumbar spine, and forearm over 24 months. Higher-level training promotes additional gains in forearm BA.

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Key words: bone mineral accrual, body composition, bone densitometry, pediatrics, artistic gymnastics

INTRODUCTION

ADAPTATIONS OF BONE to exercise are dependent in part on the magnitude and type of loading stimulus[1] and the timing of the loading exposure across the life cycle.[2,3] Maneuvers performed by artistic gymnasts produce high peak ground reaction forces and enhance bone mineral accrual.[4–6] Compared with controls, prepubescent elite-level gymnasts have higher geometric indices of bone strength in the proximal femur[7] and possess areal BMD (aBMD) values significantly higher at most skeletal sites.[8] Gymnasts in these studies began training at an early age, which might be advantageous to the skeleton. The immature skeleton is thought to be particularly responsive to exercise stimuli, because a higher rate of modeling and remodeling processes promote adaptations in the size, shape, and mineralization of bone to accommodate the loads.[9] We previously found that 3 years of gymnastics training in a group of

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early pubertal females led to aBMD gains almost 30% higher than nongymnast controls.[10]

Whereas it is evident that gymnasts who begin training early in life and advance to upper levels of competition have significantly greater BMC and aBMD compared with nonathlete controls,[10–12] it remains uncertain if advanced gymnasts are characterized by higher bone mass before the onset of their training or if the differences in aBMD result from cumulative gains with training throughout youth. The majority of gymnastics studies performed to date have examined gymnasts cross-sectionally only after they advanced to a relatively high competition level. Prospective training studies typically have been relatively short, lasting ~1 year.

To date, no published studies have examined children with limited organized sport experience before the onset of a physical activity intervention. Therefore, this study was conducted to determine the influences of the initial years of artistic gymnastics training on bone in a group of prepubertal children with essentially no organized physical activity experience before the onset of training. Novice gymnasts and comparable controls were used to help establish if selection bias is a key factor related to the high bone mass observed in gymnasts. It was hypothesized that (1) over 2 years, gymnasts would accrue bone mineral at a greater rate than nongymnasts, controlling for differences in race, pubertal stage, age, height, weight, and calcium intake, and (2) advanced, higher-level competitive gymnasts would gain more bone mineral than recreational, lower-level gymnasts.

MATERIALS AND METHODS

Design and study participants

A 24-month quasi-experimental, prospective design was used to examine the effects of recreational gymnastics activity on bone in prepubertal females from the Athens, GA area. Females, 4–8 years of age, who had essentially no previous organized physical activity (<12 weeks, considered one completed season) before beginning their first gymnastics class or nongymnastic activity, were recruited to participate ($N = 203$). To enroll in the study, participants had to have reported being healthy (reporting no history of disease or conditions known to affect bone metabolism, e.g., rickets, growth hormone deficiency, use of glucocorticoid medications) and have no evidence of secondary sexual characteristics (according to criteria for stages of breast and pubic hair development as described by Tanner[13]). Twelve cohorts of children were recruited during the winter, spring, summer, and fall seasons from fall 1997 to summer 2000. There were no seasonal differences in bone measures at baseline between those who were recruited in the summer months versus those recruited in the winter months ($p > 0.49$). At baseline, participants who were enrolling in recreational gymnastics classes 1 h/week (GYM) were compared with controls (CON) participating in nongymnastic activities or no activities. Of the 203 children who enrolled in the study, 196 completed all baseline testing. Approximately 80% completed the 2-year investigation ($n = 155$), including 65 GYM, 78 CON, and 12 participants who ceased gymnastics training and remained in the study for follow-up testing, but were not included in the statistical analyses presented here. Compared with other participants who enrolled in gymnastics, the 12 dropouts did not differ in age, height, weight, or bone mineral measures at baseline. Of the 20% who did not complete the study, 1% were found to have secondary sexual characteristics at baseline, 7% dropped out because of relocation, 10% because of noncompliance with the gymnastics program, and the remaining 3% because of noncompliance with dietary records. The ethnic distribution of the final sample was 64% white, 27% black, 3% Asian, 2% Hispanic, 1% Indian, and 3% other (i.e., biracial). Within the GYM group, 47 participants were white and 12 were black, whereas in the CON group, 44 and 26 were white and black, respectively. Among GYM, baseline bone area and mineral values were significantly higher in the black females at all skeletal sites ($p < 0.05$). Among CON, however, baseline values differed only for total body BMC and aBMD, lumbar spine BMC and aBMD, total proximal femur aBMD, and forearm bone area BMC and aBMD (black > white; $p < 0.05$).

Participants were recruited using radio and television advertisements, flyers distributed to pediatrician's offices, elementary schools, and day care centers in the community, and through electronic and/or paper flyers and newsletters sent to faculty and staff at The University of Georgia. Gymnasts were enrolled in one of three beginning-level gymnastics programs in the Athens area and trained an average of 1 h/week at baseline. Introductory classes were limited to 15 students each and included a 15-minute warm-up of stretching and light activities, followed by rotations of approximately equal time on uneven bars, vault, balance beam, and floor exercises. Gymnasts did not participate in other organized sport activities throughout the 2-year study. Monetary incentives for recruitment and participation were provided equally for each child.

Procedures

The study protocol was approved by The University of Georgia Institutional Review Board for Human Subjects. Informed assent and consent were obtained from each child and her parent, respectively. Testing procedures were completed at baseline and 6, 12, 18, and 24 months in the Bone and Body Composition Research Laboratory and University Health Services at The University of Georgia. On the day of testing, anthropometric measures and DXA procedures were performed. In addition, participants and their parent(s) completed self-administered questionnaires regarding demographic information and physical activity and were instructed on the at-home completion of 3-day diet records and use of accelerometers.

Anthropometric measures

Anthropometric measures were conducted according to the Anthropometric Standardization Reference protocol.[14] Weight of each participant, wearing light outdoor clothing without shoes, was measured to the nearest 0.25 kg using a calibrated double-beam balance scale (Fairbanks Scales, Kansas City, MO, USA). Stature was measured without shoes to the nearest 0.10 cm using a wall-mounted stadiometer (Novel Products, Rockton, IL, USA). Sitting height was measured with each participant seated on a box 50 cm in height using the same stadiometer, and estimations for leg length were calculated using standing height minus sitting height. In our laboratory, one-way random effects model, single measure intraclass correlation (ICC) coefficients were computed for anthropometric procedures in females 6–10 years of age ($n = 10$). These participants were measured by the same individual twice in a 2-week period, and the ICC (R value) as well as test-retest CV (%) values were as follows: standing height (0.99 and 0.4%), body weight (0.99 and 1.4%), and sitting height (0.97 and 0.9%), respectively. Body mass index (BMI; kg/m^2) values were plotted on BMI-for-age charts[15] to determine BMI percentiles for each child.

Sexual maturation

Sexual maturation was assessed annually by a physician using criteria for stages of breast and pubic hair development (stages I–V) as described by Tanner.[13] Prepubertal is considered stage I (no evidence of breast or pubic hair development), and early pubertal is indicated by stages II to III (evidence of development).[16] In our laboratory, one-way random effects model, single measure ICCs revealed perfect agreement ($r = 1.0$) for physician-assessed breast and pubic hair development in females 6–10 years of age ($n = 10$) from this study, evaluated by the physician twice in a 2-week period.

Bone mineral and body composition measures

aBMD (g/cm^2), BMC (g), and bone area (BA; cm^2) of the total body, lumbar spine, nondominant total proximal femur, and nondominant forearm were determined by DXA (QDR-1000W; Hologic, Waltham, MA, USA). Limb dominance was decided based on parental reports and child demonstrations of handwriting. The lumbar spine analysis was performed using DXA Low Density Spine software, whereas total body bone and body composition (including fat mass [g], percent fat, and fat-free soft tissue mass [FFST; g]) measures were determined using DXA Pediatric Whole Body Analysis software. Each total proximal femur scan was analyzed by the same individual according to standard protocol described by the manufacturer. Because of the complexity of assessing proximal femur aBMD in young children during growth,[17] the protocol for placing the region of interest is described here. The lower border of the region of interest was placed 10 spaces below the lesser trochanter (or twice the length of the greater trochanter if not visible), 5 spaces outside the edge of the greater trochanter, 5 spaces outside the edge of the femoral head, and 5 spaces above the edge of the femoral head. On each scan, the ischium was deleted before the densitometry values were calculated. The region of interest increased with each measurement period, incrementally with growth. The femoral neck box was most often placed according to the default, but in the cases of especially young children (e.g., 4 years of age), where the femoral neck was not automatically recognized by the software, the left upper corner was placed in direct contact with the greater trochanter, and in few instances, the width of the box was reduced to avoid inclusion of the head of the femur.

Participants wore light clothing and removed all metal items before being scanned. Quality assurance for DXA was carried out by daily calibration against the standard phantom provided by the manufacturer. A lumbar spine phantom containing calcium hydroxyapatite and epoxy sections embedded in a lucite cube (Hologic x-caliber anthropometric spine phantom, model DPA/QDR-1) was scanned each morning before testing. A CV of 0.27% was observed in our laboratory from 365 scans of the spine phantom over a 5-year period. Quality control for soft tissue measurements was assured by concurrently scanning (with each total body scan) an external three-step soft tissue wedge composed of different thickness levels of aluminum and lucite, calibrated against stearic acid (100% fat) and water (8.6% fat; Hologic). In our laboratory, one-way random effects model, single measure ICCs were calculated in young females 5–8 years of age ($n = 10$), scanned twice during a 1-week period for BMC and aBMD of the total body, lumbar spine, proximal femur, and forearm (all $R \geq 0.98$ and 0.95, respectively) and for percent fat ($R = 0.99$). Test-retest measurements using DXA showed the following CVs for aBMD: total body, 1.2%; lumbar spine, 1.3%; total proximal femur, 1.6%; and forearm, 2.1%; and percent fat, 2.0%.

Dietary intake measures

Dietary intake was estimated using 3-day diet records, distributed to each participant for home completion. Each parent, with assistance from their child, completed the diet record for 2 weekdays and 1 weekend day. To familiarize participants and parents with portion size estimations, a 24-h recall was administered using 3D plastic food models. All data generated from the 3-day diet records were analyzed by the same individual using Food Processor Nutrition and Dietary Analysis System (Version 7.9; ESHA Research, Salem, OR, USA). Dietary supplements of calcium and vitamin D were added subsequently to the dataset. Nutrient intakes generated from the 3-day diet record have been shown to correlate highly with direct observation ($r = 0.78$–0.94) in 9- to 10-year-old females.[18] In our laboratory, one-way random effects model, average measure (i.e., 3 days) ICCs were conducted for dietary intake estimates in female children 6–10 years of age ($n = 10$), whose 3-day diet records were completed twice in a 2-week period, and are calculated for energy ($R = 0.47$), calcium ($R = 0.71$), and vitamin D ($R = 0.94$).

Physical activity assessment

Physical activity was quantified objectively and subjectively using accelerometry (model 7164; Computer Science Applications [CSA]; Fort Walton Beach, FL, USA) and a modified version of a questionnaire developed by Slemenda et al.,[19] respectively. Accelerometers were protected in a zippered pouch worn by each child at the waist on the midaxillary line for 3 days (2 weekdays and 1 weekend day). Parents were instructed to complete a data-recording sheet indicating the periods of time when the monitor was fastened or removed from the child. Data were recorded by the CSA device during 1-minute epochs. Three-day averages for activity counts per minute were generated for each subject. Reliability data have been reported by Janz et al.[20] and Trost et al.[21] ($r = 0.69$ and 0.70, respectively) using 3- to 5-day averages in young children. The CSA monitor has also been shown to be a valid device for the assessment of children's physical activity using energy expenditure measured by calorimetry ($r = 0.87$).[22] Because the coaches in gymnastics and other organized sport activities discouraged the use of accelerometers during classes for safety reasons, each child was instructed to remove the monitor during participation in organized activities so that only leisure time physical activity would be recorded.

Organized gymnast and control activities were quantified using the self-report questionnaire by Slemenda et al.[19] Prior research with this questionnaire has provided evidence of its reliability.[19] The questionnaire was interviewer-administered to each child and her parent by trained researchers. Participants were asked to recall the time spent in after-school organized activities only. A five-point Likert scale was completed by each parent and served as an additional measure of physical activity. On this scale, parents indicated their child's usual activity level relative to childhood peers. The questionnaire consists of numerical responses indicating levels of physical activity compared with other children: 1 = much less, 2 = less, 3 = same, 4 = more, and 5 = much more. Slemenda et al.[19] showed that parental estimates of their children's activities were positively correlated with aBMD at the hip and spine. In addition to self-report, select gymnastics classes (i.e., low level and high level) were video recorded and monitored by trained observers for quantification of the type, frequency, and duration of elements performed. Last, classes were monitored for compliance by coaches at the gymnastics facilities, who submitted attendance records after each session.

Statistical analyses

Data were analyzed using SPSS (version 11.0.2; SPSS) and S-PLUS (version 6.1.2; Insightful Corp.). Independent samples *t*-tests were conducted for all baseline measures. Nonlinear mixed effects models based on four-parameter logistic sigmoidal growth curves were used to address hypothesis 1. The four-parameter logistic curve is given by:

$$y = e^{\theta_0} + \frac{\theta_1 - e^{\theta_0}}{1 + \exp[(\theta_2 - x)/\theta_3]} + \varepsilon$$

where x is age, and y is the response at age x. Such a curve has a sigmoidal shape with left (lower) asymptote at e^{θ_0} and right (upper) asymptote at θ_1. The parameter θ_2 has an interpretation as the x value (i.e., the age) at which the response has reached $\theta_1/2$, or one-half of its ultimate expected size, and θ_3 is a parameter that scales the x-axis. That is, θ_3 quantifies the rate of increase over time in the mean of y. Figure 1 shows the logistic curve including parameter interpretations. The main outcomes of interest are to determine (1) differences in the asymptote parameterθ_1 and (2) differences in the growth rate parameter θ_3 between the groups.

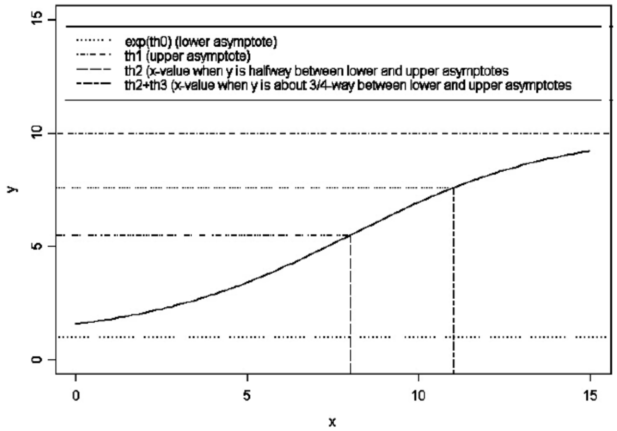

FIG. 1. An example of the four parameter logistic curve with components th0, th1, th2, and th3 (0, 10, 8 and 3, respectively).

The resulting models were used to compare the baseline and postbaseline responses of the participants, and covariates were used to control for differences among the study groups at baseline. To account for baseline differences among the participants in the two groups and to account for correlation among the repeated measurements within a subject, θ_0, θ_1, θ_2, and θ_3 are modeled as mixed effects, that is, as linear functions of baseline covariates and subject-specific random effects. These nonlinear mixed effects models are described in detail by Pinheiro and Bates.[23] In addition to controlling for subject variability between groups at baseline, other covariates considered important with respect to bone changes over time were included in the model: race, baseline measures of body mass, height, and calcium intake, and change in breast development beyond stage II at 24 months.[19,24–26] Significance tests and plots of the random effects versus potential covariates were used to aid the covariate selection process. Effect sizes calculated for group comparisons are expressed as *t*-statistics (parameter estimates divided by their SE).

To test hypothesis 2, that higher-level gymnasts advancing to competition (HLG; $n = 9$) will show greater gains in bone mineral compared with lower-level gymnasts who did not advance (LLG; $n = 56$), the overall sample of the GYM group was divided into high versus low level based on the number of hours of participation in gymnastics activity. A histogram of raw hours of gymnastics classes (over the 24-month testing period) was completed and revealed a bimodal frequency distribution, where two distinct groups emerged: one lower (<100 h; mean = 63 h over 2 years; 1.24 ± 0.63 h/week) and one higher activity (>100 h; mean = 259 h over 2 years; 7.89 ± 3.05 h/week; see Fig. 2). Additionally, HLG performed more difficult maneuvers compared with LLG, as described in Table 1.

RESULTS

Anthropometric measures

Participant characteristics for baseline and 2-year measures are presented in Table 2. Children enrolling in the

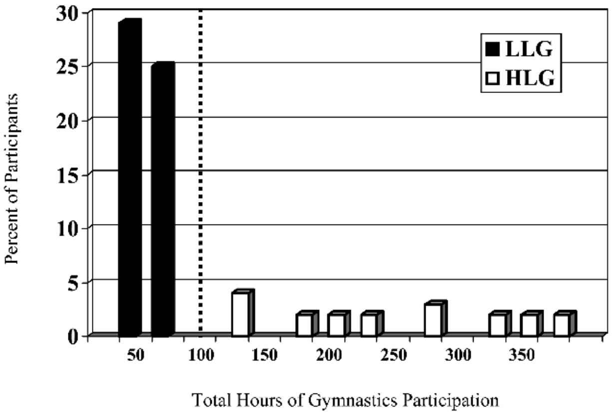

FIG. 2. Frequency distribution of total hours of gymnastics participation over 2 years. Dashed line represents designation for low-level gymnasts (LLG; <100 h) and high-level gymnasts (HLG; >100 h).

GYM group at baseline were significantly shorter and lighter versus those in the CON group and had lower measurements of sitting height and leg length ($p < 0.05$). Gymnasts also had significantly lower BMI-for-age percentiles[15] compared with CON (58.8 ± 25.3 versus 69.2 ± 27.5; $p < 0.02$).

Sexual maturation

By design, each eligible participant was classified as pubertal stage I for both breast and pubic hair development on study entry. However, by the conclusion of the study, 11 GYM and 25 CON advanced beyond stage I, displaying some evidence of secondary sex characteristics for early pubertal breast and pubic hair development (i.e., stages II–III). Whereas advancement in pubertal stage did occur in these individuals, menarche was not achieved during the course of the study for any of the subjects.

Bone mineral and body composition measures

Baseline absolute values of bone mineral are presented in Table 2 and reveal lower aBMD, BMC, and BA in GYM versus CON at the total body, lumbar spine, and forearm (all $p < 0.05$). Furthermore, GYM had significantly lower fat mass, FFST, and percent fat than CON (all $p < 0.05$). High-level gymnasts did not differ significantly in these measurements compared with LLG ($p > 0.05$). Unadjusted values presented in Table 2 suggest that GYM remained lower in bone mineral measures after 2 years; however, after adjusting the data for initial differences, it was determined that GYM had greater BA, BMC, and aBMD responses compared with CON at some skeletal sites. Table 3 summarizes the main results from the nonlinear mixed effects models for 24-month changes in BA, BMC, and aBMD by displaying effect sizes. The upper asymptote of the mean response was estimated to be significantly higher in GYM for total body aBMD and forearm BMC compared with CON ($p < 0.04$) based on the 2-year data from this study. There was no significant difference between HLG and LLG with respect to this parameter. Compared with CON over 2 years, GYM had a significantly greater rate of increase in the mean response of lumbar spine aBMD and forearm BA ($p < 0.01$). To show these differences in the lumbar spine and forearm, Fig. 3 serves as an example of the observed data and predicted growth curve responses over 2 years in a representative GYM and CON participant, 5 years of age at baseline. High-level gymnasts proceeded to an advanced/competition level after 6–12 months of gymnastics participation. When comparing HLG versus LLG over the 2 years, HLG increased at a faster rate than LLG in BA of the forearm ($p < 0.01$).

Lumbar spine aBMD data were further analyzed using repeated measures ANOVA in a subsample of individually matched GYM and CON subjects who remained prepubertal throughout the duration of the study ($n = 31$ per group, matched on race, age [±1 year], height [±5 cm], and weight [±3.5 kg], because groups differed on these characteristics at baseline). Gymnasts gained more aBMD at the lumbar spine ($p = 0.03$; $\eta^2 = 0.47$ for the group × time interaction) than CON over 2 years. Using Schwarzer's Meta 5.3 software to convert the η^2 measure of effect size to the same metric (r), a t-statistic of 2.84 converted to $r = 0.23$, whereas the group × time interaction converted to $r = 0.18$.

TABLE 1. SELECTED ARTISTIC GYMNASTICS ELEMENTS OBTAINED BY DIRECT OBSERVATION FOR LOW-LEVEL AND HIGH-LEVEL CLASSES

Elements	*Number*
Low-level*	
Pike, tuck, straight, and straddle jumps on long trampoline	18
Full turn, pike, tuck, straight, and straddle jumps on floor	13
Stick drills	3
Hop with both feet on balance beam	3
Cartwheels on floor	2
Jump on mini-trampoline to mat below	2
Jump on springboard and bounce down to floor	2
Jump on springboard to higher object	2
Straddle jumps on circular mini-trampoline	2
High-level†	
Jumping jacks	100
Jump to straddle handstand on floor	71
Tuck jumps on floor	70
Straddle, straight, tuck, split jumps on beam	67
Pike, tuck, straight and straddle jumps on long trampoline	60
Side hops over low beam	24
Jumps up and across beam	17
Jump from high mat rebound	15
Back handsprings (consecutive)	12
Cartwheel dismount from beam onto mat	10
Cartwheel back tuck dismount on beam	7
Jumps out and across beam	7
Jump handstand over vault	4
Jump off end of beam backward	1

* Numbers are generated for an average of 10 classes that were observed and videotaped for the low-level classes.

† Numbers are generated for an average of five classes that were observed and videotaped for the high-level classes.

TABLE 2 PARTICIPANT CHARACTERISTICS AT BASELINE AND 2 YEARS

	Baseline		2 Years	
	Gymnasts (n = *65*)	*Controls* (n = *78*)	*Gymnasts* (n = *65*)	*Controls* (n = *78*)
Age and Anthropometry				
Chronological age (years)	6.0 ± 1.49	6.3 ± 1.57	8.1 ± 1.49	8.3 ± 1.58
Height (cm)	115 ± 10.3*	119 ± 11.8	128 ± 10.8*	133 ± 11.6
Weight (kg)	21.5 ± 5.10*	25.2 ± 7.60	28.7 ± 7.57*	34.8 ± 11.5
BMI (kg/m^2)	16.1 ± 1.67*	17.3 ± 2.88	17.2 ± 2.51*	19.2 ± 4.18
Sitting height (cm)	62.5 ± 4.60*	64.5 ± 5.49	69.5 ± 4.82*	72.1 ± 5.59
Leg length (cm)	52.4 ± 6.31*	54.9 ± 6.85	58.8 ± 6.44*	61.2 ± 6.48
Dietary intake				
Energy (kcals)	1653 ± 467	1679 ± 371	1749 ± 364	1724 ± 434
Calcium (mg)	837 ± 436	847 ± 337	887 ± 405	805 ± 323
Vitamin D (μg)	9.4 ± 6.3	8.4 ± 5.5	9.5 ± 6.1	8.0 ± 5.8
Accelerometry				
Counts per minute	773 ± 196	769 ± 204	752 ± 325	758 ± 300
Body composition				
Fat mass (g)	5050 ± 2391*	7227 ± 4485	7201 ± 4098*	10873 ± 7026
Lean mass (g)	14891 ± 3228*	16384 ± 3873	19459 ± 4670*	21567 ± 5302
Fat (%)	23.9 ± 6.97*	27.7 ± 9.29	24.9 ± 8.83*	29.8 ± 10.93
Total body				
BA (cm^2)	1116 ± 197*	1236 ± 256	1392 ± 247*	1545 ± 314
BMC (g)	729 ± 186*	840 ± 245	997 ± 255*	1151 ± 323
aBMD (g/cm^2)	0.646 ± 0.06*	0.669 ± 0.06	0.708 ± 0.06*	0.736 ± 0.07
Lumbar spine				
BA (cm^2)	28.6 ± 4.23*	30.6 ± 5.14	34.1 ± 50.5*	36.6 ± 6.17
BMC (g)	15.3 ± 3.54*	17.2 ± 4.61	20.5 ± 5.47*	22.6 ± 6.24
aBMD (g/cm^2)	0.530 ± 0.05*	0.557 ± 0.07	0.592 ± 0.08	0.609 ± 0.08
Total proximal femur				
BA (cm^2)	15.0 ± 3.37*	16.6 ± 4.03	18.8 ± 4.04*	20.4 ± 4.53
BMC (g)	9.09 ± 2.99*	10.5 ± 3.53	12.5 ± 4.07*	14.1 ± 4.56
aBMD (g/cm^2)	0.594 ± 0.08	0.620 ± 0.08	0.655 ± 0.08	0.680 ± 0.09
Forearm				
BA (cm^2)	5.76 ± 1.25*	6.43 ± 1.41	7.39 ± 1.58*	8.05 ± 1.80
BMC (g)	2.04 ± 0.64*	2.36 ± 0.72	2.85 ± 0.85*	3.19 ± 0.97
aBMD (g/cm^2)	0.348 ± 0.04	0.361 ± 0.04	0.381 ± 0.04	0.391 ± 0.04

Values are unadjusted means ± SD.
* Significant difference ($p < 0.05$) between gymnasts and controls.

Dietary intake measures

Intakes of energy, calcium, and vitamin D were similar at baseline and did not change over the 2 years. Forty-one GYM and 35 CON reported regular use of a children's multivitamin supplement. For both GYM and CON groups, baseline mean vitamin D and calcium intakes (Table 2) met or exceeded the adequate intake (AI) recommendations for children 4–8 years of age.[27] Six GYM and five CON had individual estimated calcium intakes <50% (400 mg/day) of the AI, whereas 12 GYM and 11 CON had estimated vitamin D intakes <50% (2.5 μg/day) of the AI.

Physical activity assessment

Baseline average activity counts per minute obtained using CSA accelerometers were not different between groups (Table 2). Once enrolled in the study, both GYM and those CON who participated in other youth sport activities did so for ~1 h/week based on results from the activity questionnaire[19] (Table 4). Gymnasts attended an average of 78.7 ± 10.9% of scheduled classes (obtained from attendance records). At baseline, the average score on the parent-rated Likert scale of activity was 3.7 ± 0.7 for GYM and 3.4 ± 0.7 for CON, indicating no significant differences between groups. Using Spearman rank-order correlations for the combined GYM and CON groups, baseline parental Likert scale ratings were significantly and positively correlated with total body aBMD ($\rho = 0.25$; $p = 0.05$) and negatively correlated with fat mass ($\rho = -0.34$; $p < 0.001$) and percent fat ($\rho = -0.36$; $p < 0.001$).

DISCUSSION

This is the first prospective report of bone mineral changes in young children with essentially no prior structured physical activity participation. The primary finding was that, over 2 years, young females participating in their first recreational gymnastics class showed a significantly greater rate of increase in the mean response of lumbar spine aBMD and forearm BA compared with those who did not enroll in gymnastics. It was also observed that forearm BA increased at a faster rate in HLG compared with LLG who remained at the noncompetitive level. In addition, the long-term (asymptotic) mean response for total body

TABLE 3. NONLINEAR MIXED EFFECTS MODEL RESULTS FOR CHANGES IN BONE AREA, BMC AND aBMD OVER 2 YEARS IN (A) GYMNASTS (N = 65) VS. CONTROLS (N = 78) AND (B) HIGH-LEVEL GYMNASTS (N = 9) VS. LOW-LEVEL GYMNASTS (N = 56)

	Growth rate parameter		*Asymptote parameter*	
	*A**	*B**	*A*†	*B*†
Total body				
BA (cm^2)	0.49	0.67	0.23	0.43
BMC (g)	1.88	0.74	0.58	0.37
aBMD (g/cm^2)	1.42	0.03	1.71‡	1.01
Lumbar spine				
BA (cm^2)	0.34	0.21	0.37	0.02
BMC (g)	–0.47	0.10	–0.11	0.47
aBMD (g/cm^2)	–2.84‡	–0.84	–1.79	–0.42
Total proximal femur				
BA (cm^2)	<0.01	0.73	–1.33	–1.21
BMC (g)	–1.10	0.34	–0.51	0.20
aBMD (g/cm^2)	–0.17	0.65	0.69	1.24
Forearm				
BA (cm^2)	–5.49‡	–6.28§	–4.29	–5.70
BMC (g)	1.14	0.94	2.34‡	1.28
aBMD (g/cm^2)	–0.56	0.17	–0.52	0.35

Values are effect sizes (t-statistics).

* Negative value corresponds to expected direction of effect (benefit of gymnastics training/high-level gymnastics training).

† Positive value corresponds to expected direction of effect (benefit of gymnastic training/high-level gymnastics training).

‡ Significant difference from controls ($p < 0.05$).

§ Significant difference from low-level gymnasts ($p < 0.05$).

aBMD and forearm BMC was estimated to be higher for GYM than for CON. These results suggest that beginning-level maneuvers performed in introductory gymnastics classes seem to be adequate stimuli for enhancing gains in both bone mineral and size, particularly at the lumbar spine and forearm, but not at the hip.

It has been shown that competitive collegiate,[11,28] adolescent,[12,29] and retired[8,30] artistic gymnasts have considerably higher bone mineral measures at nearly all skeletal sites compared with nongymnast controls similar in age, height, and weight. These higher bone values could be the result of cumulative gains with years of training, higher bone mass at the onset of the sport, or both. In more recent years, it has been documented that gymnasts initiate training as young as 3–4 years of age,[31] exposing the skeleton to years of high load stimuli. A 3-year observational study of adolescent females (10.5 ± 1.5 years of age at baseline) revealed that competitive nonelite gymnasts who already had significantly higher aBMD than controls at all skeletal sites measured[12] were able to acquire additional gains in hip and total body aBMD and lumbar spine BMC with continued training, accumulating up to 30% beyond gains in controls.[10] Results from this study also support this hypothesis of cumulative aBMD gains at the lumbar spine over time. Studies in junior tennis players present important findings, showing side-to-side differences in loaded versus nonloaded arms,[32,33] further supporting the conjecture that high-load activities promote cumulative gains in bone mineral with years of training.

Alternatively, the higher rates of bone mineral accrual in gymnasts may be the result of a genetically inherited stronger skeleton rather than the mode of activity.[34] This study sought to determine if there was a relationship between self-selection and bone mineral accrual in young gymnasts before the onset of training. The study design allowed the examination of anthropometric, dietary, bone, and body composition measures of all participants before the onset of gymnastics or other organized activity involvement. Because other investigations of child gymnasts were conducted at least 1 year after initiating the sport,[6,8,35] it would be impossible to determine how the bone mineral measures of gymnasts compared with nongymnast controls at the start of training. In this study, differences existed between groups at the onset, where GYM were significantly shorter, lighter, and leaner than CON; therefore, there could have been bias introduced into the study based on self-selection. To our knowledge, only one report, a retrospective study of female elite gymnasts, has shown that individuals who select gymnastics activity are generally smaller and leaner than controls before participation.[36] In this study, the majority of bone mineral values were also lower in GYM versus CON at baseline, indicating that the skeletal benefits were presumably caused by the activity and not a "denser" skeleton at the onset of training.

Absolute values presented in Table 2 imply that GYM remained lower in bone mineral measures 2 years after initiating the sport; however, after adjusting the data for initial differences, GYM actually had increased rates of forearm BA and lumbar spine aBMD compared with CON. This greater rate of increase in the mean response of lumbar spine aBMD after 2 years of gymnastics training in this study corresponds with findings of shorter-duration childhood interventions that implemented jumping programs of high-impact forces to the skeleton similar to those produced by gymnastics training.[4,37] Fuchs et al.[4] observed a significant increase in the intervention group compared with controls for aBMD of the lumbar spine using a sample of prepubertal boys and girls 6–10 years of age. This protocol consisted of a progressive in-school program of 10 minutes of jumping three times per week. In contrast, no differences were reported at the spine for prepubertal children (stage I; mean age, 10.1 years) undergoing a similar jumping program, consisting of 12 minutes of jumping three times per week.[37] Although training was progressive in this program, the intensity of the jumping may not have been high enough to elicit a response at the lumbar spine, as shown by Fuchs et al.[4] However, in early pubertal children (stage II–III; mean age, 10.5 years),[37] a skeletal response did occur; participants in the jumping intervention showed significantly greater gains in lumbar spine aBMD over controls (1.7%) after 7 months. Over 20 months, MacKelvie et al.[38] also found that BMC gains were cumulative in females (pubertal stages I–III; mean age, 8.8–11.7 years at baseline), up to 3.7%, after a jumping exercise intervention incorporated into physical education classes.

In this study, BA of the forearm increased at a greater rate in GYM versus CON and in HLG versus LLG, indicating that either the mode and/or the frequency of gym-

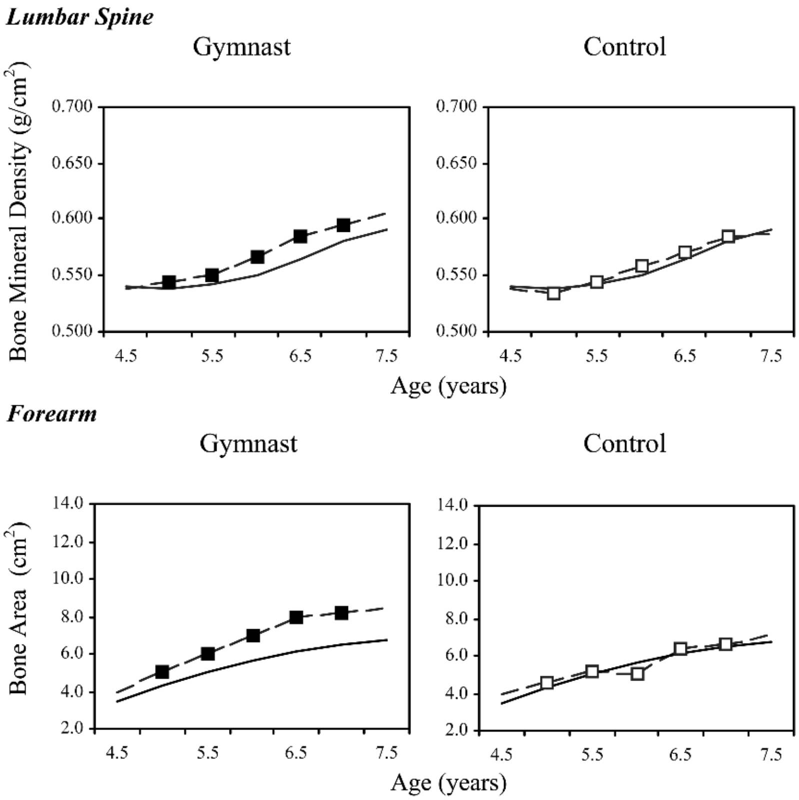

FIG. 3. Illustration of observed data (—) and predicted growth curves (- - -) at the lumbar spine and forearm using a representative from the gymnast (■) and control (□) groups, 5 years of age at baseline.

nastics participation at an early age led to an increase in bone size. Whereas differences were expected to emerge at the proximal femur between GYM versus CON and HLG versus LLG, no changes in the rate of bone mineral accrual between groups at this site were observed. Greater differences in BMC were also expected to emerge at all skeletal sites in GYM versus CON and HLG versus LLG. A possible reason for lack of BMC group differences at the lumbar spine and BMC and aBMD differences at the forearm and proximal femur is that the exercise protocols were not as strenuous as the training schedule of the older, elite gymnasts studied previously. Scerpella et al.[39] reported a dose-response to gymnastics training in prepubescent females by comparing high- (>8 h/week) and low- (1–8 h/week) level gymnasts, where differences in the total and regional aBMD (i.e., forearm and hip) measures were found to be greater in the high-level gymnasts.[39] Based on direct observation of selected classes in this study (Table 1), GYM participating in the high-level classes performed more difficult maneuvers than those in the low-level classes, likely generating higher ground reaction forces on the skeleton. Whereas these more advanced maneuvers would have been expected to load the skeleton and promote greater BMC and aBMD gains, it is likely that an even greater strain magnitude, rate, or duration of activity in the elite gymnasts may have been necessary to elicit a geometric conformation of bone and enhanced rates of bone mineral deposition at these skeletal sites, beyond what was achieved by recreational gymnasts in this study.[31] As evidenced by observations in older children,[37,38] it is possible that the positive effect of gymnastics participation on bone mineralization in the skeletal sites measured will emerge as the participants become more developmentally mature and/or advance to a more competitive training level, engaging in activities that promote a greater effect on the skeleton.[31]

Assessment of bone mineral accrual with exercise studies is limited, however, because important changes in the geometric properties of bone may occur and go undetected. For example, the primary outcome measures in this study, BMC and aBMD, do not account for changes in the shape and structure of bone. Because modeling during growth can alter endosteal and periosteal dimensions,[40] measures of the structural properties of bone in addition to bone mineral may have provided valuable information. Studies in children using the hip structural analysis program[41] to detect geometric and strength changes in bone have shown higher indices of cross-sectional area (an index of axial strength) and section modulus (an index of bending strength) in elite gymnasts[7] and in children after a 7-month jumping intervention.[40]

The development of the skeleton is characterized by distinctive biological phases and differing sequential patterns of growth in bone size and mass that are linked to hormonal regulation.[1,9] A principal strength of this study was the deliberate recruitment of children who were prepubertal, within the age range of 4–8 years. The purpose of employing these selection criteria was to limit variability within physiological characteristics acknowledged for their effects on the immature skeleton.[42,43] Whereas groups differed at baseline concerning height, weight, sitting height, and leg length, there were no differences in how these variables changed over 2 years in GYM versus CON. This was ex-

TABLE 4. PARTICIPATION IN ACTIVITIES BY THE CONTROLS OVER 2 YEARS

Activity	*Number participating*	*Duration (hours)*
None	46	0
Light/sedentary		
Girls club	6	4
Piano	1	4
Brownies/girl scouts	1	2
Bible camp	1	1
Moderate/vigorous		
Dance	20	1.5
Basketball	8	3
Soccer	6	2
Swimming	6	1
Softball/tee-ball	4	3
Horseback riding	4	1
Cheerleading	3	3
Karate/taekwondo	3	1
Tennis	2	1
Twirling/baton	2	0.5

Values indicate participation (n) and duration (average hours per week) in organized after-school activities at any given time throughout the 24-month study period.

pected, because recreation-level artistic gymnastics initiated at a young age would be presumed to not interfere with normal growth velocity, unlike the growth aberrations suspected in elite-level gymnasts.[8,44] However, longer-term studies following young females from the onset of gymnastics training throughout their growth spurt, as the intensity and duration of training intensifies, are needed to further explicate this relationship.

A key factor that could potentially account for group differences in bone mineral accrual is dietary calcium.[45–47] Dietary calcium intake is an important determinant of lumbar spine aBMD among children and adolescents.[45–49] Inadequate dietary calcium in children has been estimated to account for a difference of 1 SD (~10%) in bone mass accrual by the age of 18 years.[16] Two recently published randomized trials[50,51] showed that over 8–12 months, calcium intake modified the bone response to activity in young children. Iuliano-Burns et al.[51] suggest that the effects of exercise are site-specific, whereas the effects of calcium supplementation are likely generalized. Both studies emphasize the importance of calcium in the diet with respect to bone health in young children. Dietary intakes of GYM and CON in this study did not differ at baseline or over 2 years. The similarity between groups is consistent with prior reports in child gymnasts.[6,35,52] Furthermore, both groups of participants met the dietary reference intake recommendations for U.S. children for energy,[53] calcium, and vitamin D.[27] These findings suggest that the higher bone gains in GYM versus CON were not influenced by the participants' calcium intakes, nor did gymnastics training alter dietary calcium intakes over time. It is unknown, however, if intakes higher than those consumed by participants in this study would have potentiated the effects of gymnastics training on bone mineral accrual.

Physical activity assessed with accelerometry was similar between groups for leisure time activity. This study did not capture physical activity measured by the CSA device for participants during organized sport, which was a limitation of this assessment. However, data from this study are similar to those reported by Janz et al.,[54] where the total activity counts were 701 ± 160 average counts/minute for non-athletic young females. Physical activity measured by accelerometry has shown to positively correlate with bone measures in preschool children.[54] In this study, parental Likert scale ratings obtained through questionnaire were significantly and positively correlated with total body aBMD and negatively correlated with percent fat and fat mass. Similarly, it has been shown that children above the median of mothers' activity rating had significantly greater aBMD at the hip and spine.[19]

Children in this study were not randomized to the gymnastics intervention. While it is acknowledged that causality cannot be proven in observational studies,[34] careful consideration was given to the young age of the children and the likelihood that randomization into an after-school youth sport program for 2 years would have been unfeasible and resulted in a much higher participant attrition rate. Children were given the option to enroll in either the GYM group (beginning gymnastics classes) or the CON group (participate in other sports or no sports) for the duration of the study. The compliance with this community intervention study was ~80%. Although slightly lower than the compliance of other exercise interventions in children (86–100%),[4,55] the duration of this intervention was more than twice as long.

It is well recognized that prospective pediatric bone studies are confounded by changes in maturational status.[38] To account for this potential confounding and bias associated with observational studies, several variables important to bone mineral accrual in children were controlled for on which the GYM and CON groups may have differed at baseline. This was done by incorporating these variables as covariates in nonlinear mixed effects models that describe the relationship between the mean response and age in terms of a sigmoidal growth curve. This approach was chosen in preference to more traditional methods for longitudinal data analysis such as the repeated measures ANCOVA,[56] which describes the mean response for each group by measurement occasion combination as a polynomial function of covariates. Two major drawbacks of such an approach for this study are (1) the natural ordering of observations through time is ignored, because the mean response is not modeled as a function of time, and (2) the groups measured at each time-point were heterogeneous with respect to age so that the group mean at a particular time point is not particularly meaningful in terms of growth and development. Instead, the nonlinear mixed modeling approach describes the mean response as a function of age rather than time for each subject, and attempts to place each subject's response over time profile at an appropriate place along an underlying growth trajectory assumed to be of sigmoidal form (Fig. 1). Time-invariant features of this growth curve, such as the asymptote and growth rate, can then be compared between groups while controlling for potential confounders through the inclusion of covariates in the model. To strengthen the rationale for use of the four-parameter logistic growth curve modeling, lumbar spine aBMD data were analyzed using the traditional repeated measures ANOVA in a subsample of individually matched GYM and CON. Similar to the results determined by growth curve modeling, GYM gained significantly more aBMD at the lumbar spine than CON over 2 years. The calculated effect size for detecting differences between groups was determined to be slightly larger using the growth curve modeling.

Because more active children may emerge from adolescence with ~5–10% greater bone mass depending on the skeletal site, this may signify an important biological advantage in terms of attaining optimal skeletal health and prevention of future fractures.(19) It has been considered that high loads on the skeleton are the most important exercise factors related to bone development.(54) Data from this study support this idea in a group of nonelite, introductory-level female gymnasts. Although some exercise intervention studies point to early-mid puberty as a more opportune time for enhancing childhood bone, rather than during prepuberty,(37,40) in this study, prepubertal recreational-level gymnasts achieved greater rates of increases in lumbar spine aBMD and forearm BA compared with controls. Furthermore, those gymnasts who advanced to a higher level of training gained more BA at the forearm compared with those who remained at the lower level. It was recently acknowledged that, to determine the effects of gymnastics on growth, maturation, and skeletal development, "well-controlled prospective longitudinal studies, possibly starting at birth or at least before entry to the sport, are required."(57) While these results provide a representation of young female's physical characteristics before beginning their sport, there remains a clear necessity for longer-term exercise intervention studies extending through the complete maturational period. A study of this nature will help contribute to our understanding of the timing of bone gains during childhood with lifestyle interventions and of whether a "critical period" indeed exists with respect to optimal bone mineral accrual through exercise.

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REFERENCES

1. Bass SL 2000 The prepubertal years: A uniquely opportune stage of growth when the skeleton is most responsive to exercise? Sports Med **30:**73–78.
2. Modlesky CM, Lewis RD 2002 Does exercise during growth have a long-term effect on bone health? Exerc Sport Sci Rev **30:**171–176.
3. MacKelvie KJ, Khan KM, McKay HA 2002 Is there a critical period for bone response to weight-bearing exercise in children and adolescents? a systematic review. Br J Sports Med **36:**250–257.
4. Fuchs RK, Bauer JJ, Snow CM 2001 Jumping improves hip and lumbar spine bone mass in prepubescent children: A randomized controlled trial. J Bone Miner Res **16:**148–156.
5. McKay HA, Petit MA, Schutz RW, Prior JC, Barr SI, Khan KM 2000 Augmented trochanteric bone mineral density after modified physical education classes: A randomized school-based exercise intervention study in prepubescent and early pubescent children. J Pediatr **136:**156–162.
6. Nickols-Richardson SM, O'Connor PJ, Shapses SA, Lewis RD 1999 Longitudinal bone mineral density changes in female child artistic gymnasts. J Bone Miner Res **14:**994–1002.
7. Faulkner RA, Forwood MR, Beck TJ, Mafukidze JC, Russell K, Wallace W 2003 Strength indices of the proximal femur and shaft in prepubertal female gymnasts. Med Sci Sports Exerc **35:**513–518.
8. Bass S, Pearce G, Bradney M, Hendrich E, Delmas PD, Harding A, Seeman E 1998 Exercise before puberty may confer residual benefits in bone density in adulthood: Studies in active prepubertal and retired female gymnasts. J Bone Miner Res **13:**500–507.
9. Bass S, Delmas PD, Pearce G, Hendrich E, Tabensky A, Seeman E 1999 The differing tempo of growth in bone size, mass, and density in girls is region-specific. J Clin Invest **104:**795–804.
10. Laing EM, Massoni JA, Nickols-Richardson SM, Modlesky CM, O'Connor PJ, Lewis RD 2002 A prospective study of bone mass and body composition in female adolescent gymnasts. J Pediatr **141:**211–216.
11. Kirchner EM, Lewis RD, O'Connor PJ 1995 Bone mineral density and dietary intake of female college gymnasts. Med Sci Sports Exerc **27:**543–549.
12. Nickols-Richardson SM, Modlesky CM, O'Connor PJ, Lewis RD 2000 Premenarcheal gymnasts possess higher bone mineral density than controls. Med Sci Sports Exerc **32:**63–69.
13. Tanner J 1962 Growth and Adolescence, 2nd ed. Blackwell Scientific Publications, Oxford, UK.
14. Lohman TG, Roche AF, Martorell R 1988 Anthropometric Standardization Reference Manual. Human Kinetics, Champaign, IL, USA.
15. Kuczmarski RJ, Ogden CL, Grummer-Strawn LM, Flegal KM, Mei Z, Wei R, Curtin LR, Roche AF, Johnson CL 2002 2000 CDC growth charts for the United States: Methods and development. Vital Health Stat **246:**1–90.
16. Slemenda CW, Reister TK, Hui SL, Miller JZ, Christian JC, Johnston CC Jr 1994 Influences on skeletal mineralization in children and adolescents: Evidence for varying effects of sexual maturation and physical activity. J Pediatr **125:**201–207.
17. McKay HA, Petit MA, Bailey DA, Wallace WM, Schutz RW, Khan KM 2000 Analysis of proximal femur DXA scans in growing children: Comparisons of different protocols for cross-sectional 8-month and 7-year longitudinal data. J Bone Miner Res **15:**1181–1188.
18. Crawford PB, Obarzanek E, Morrison J, Sabry ZI 1994 Comparative advantage of 3-day food records over 24-hour recall and 5- day food frequency validated by observation of 9- and 10-year-old girls. J Am Diet Assoc **94:**626–630.
19. Slemenda CW, Miller JZ, Hui SL, Reister TK, Johnston CC Jr 1991 Role of physical activity in the development of skeletal mass in children. J Bone Miner Res **6:**1227–1233.
20. Janz K, Witt J, Mahoney L 1995 The stability of children's activity as measured by accelerometry and self-report. Med Sci Sports Exerc **27:**1326–1332.
21. Trost S, Pate R, Freedson P, Sallis J, Taylor W 2000 Using objective physical activity measures with youth: How many

days of monitoring are needed? Med Sci Sports Exerc **32:**426–431.
22. Trost SG, Ward DS, Moorehead SM, Watson PD, Riner W, Burke JR 1998 Validity of the computer science and applications (CSA) activity monitor in children. Med Sci Sports Exerc **30:**629–633.
23. Pinheiro J, Bates D 2000 Mixed-Effects Models in S and S-PLUS, 1st ed. Springer, New York, NY, USA.
24. Van Coeverden SC, De Ridder CM, Roos JC, Vant′Hof MA, Netelenbos JC, Delemarre-Van de Waal HA 2001 Pubertal maturation characteristics and the rate of bone mass development longitudinally toward menarche. J Bone Miner Res **16:**774–781.
25. Rizzoli R, Bonjour JP 1999 Determinants of peak bone mass and mechanisms of bone loss. Osteoporos Int **9**(Suppl 2)**:**S17–S23.
26. Boot AM, de Ridder MAJ, Pols HAP, Krenning EP, de Muinck Keizer-Schrama SMPF 1997 Bone mineral density in children and adolescents: Relation to puberty, calcium intake, and physical activity. J Clin Endocrinol Metab **82:**57–62.
27. Institute of Medicine 1997 Dietary Reference Intakes for Calcium, Phosphorus, Magnesium, Vitamin D, and Flouride. Food and Nutrition Board, National Academy Press, Washington, DC, USA.
28. Taaffe DR, Snow-Harter C, Connolly DA, Robinson TL, Brown MD, Marcus R 1995 Differential effects of swimming versus weight-bearing activity on bone mineral status of eumenorrheic athletes. J Bone Miner Res **10:**586–593.
29. Lehtonen-Veromaa M, Mottonen T, Svedstrom E, Hakola P, Heinonen OJ, Viikari J 2000 Physical activity and bone mineral acquisition in peripubertal girls. Scand J Med Sci Sports **10:**236–243.
30. Kirchner EM, Lewis RD, O'Connor PJ 1996 Effect of past gymnastics participation on adult bone mass. J Appl Physiol **80:**226–232.
31. Zanker CL, Gannon L, Cooke CB, Gee KL, Oldroyd B, Truscott JG 2003 Differences in bone density, body composition, physical activity, and diet between child gymnasts and untrained children 7-8 years of age. J Bone Miner Res **18:**1043–1050.
32. Haapasalo H, Kannus P, Sievanen H, Pasanen M, Uusi-Rasi K, Heinonen A, Oja P, Vuori I 1998 Effect of long-term unilateral activity on bone mineral density of female junior tennis players. J Bone Miner Res **13:**310–319.
33. Bass SL, Saxon L, Daly RM, Turner CH, Robling AG, Seeman E, Stuckey S 2002 The effect of mechanical loading on the size and shape of bone in pre-, peri-, and postpubertal girls: A study in tennis players. J Bone Miner Res **17:**2274–2280.
34. Karlsson M 2002 Does exercise reduce the burden of fractures? A review. Acta Orthop Scand **73:**691–705.
35. Courteix D, Lespessailles E, Jaffre C, Obert P, Benhamou CL 1999 Bone material acquisition and somatic development in highly trained girl gymnasts. Acta Paediatr **88:**803–808.
36. Peltenburg AL, Erich WB, Zonderland ML, Bernink MJ, Van-DenBrande JL, Huisveld IA 1984 A retrospective growth study of female gymnasts and girl swimmers. Int J Sports Med **5:**262–267.
37. Mackelvie KJ, McKay HA, Khan KM, Crocker PR 2001 A school-based exercise intervention augments bone mineral accrual in early pubertal girls. J Pediatr **139:**501–508.
38. MacKelvie KJ, Khan KM, Petit MA, Janssen PA, McKay HA 2003 A school-based exercise intervention elicits substantial bone health benefits: A 2-year randomized controlled trial in girls. Pediatrics **112:**e447.
39. Scerpella TA, Davenport M, Morganti CM, Kanaley JA, Johnson LM 2003 Dose related association of impact activity and bone mineral density in pre-pubertal girls. Calcif Tissue Int **72:**24–31.
40. Petit MA, McKay HA, MacKelvie KJ, Heinonen A, Khan KM, Beck TJ 2002 A randomized school-based jumping intervention confers site and maturity-specific benefits on bone structural properties in girls: A hip structural analysis study. J Bone Miner Res **17:**363–372.
41. Beck TJ, Ruff CR, Warden KE, Scott M, Scott WW, Rao GU 1990 Predicting femoral neck strength from bone mineral data. Invest Radiol **25:**6–18.
42. Lloyd T, Beck TJ, Lin HM, Tulchinsky M, Eggli DF, Oreskovic TL, Cavanagh PR, Seeman E 2002 Modifiable determinants of bone status in young women. Bone **30:**416–421.
43. Seeman E 2002 An exercise in geometry. J Bone Miner Res **17:**373–380.
44. Caine D, Bass S, Daly R 2003 Does elite competition inhibit growth and delay maturation in some gymnasts? Quite possibly. Pediatr Exerc Sci **15:**360–372.
45. Ruiz JC, Mandel C, Garabedian M 1995 Influence of spontaneous calcium intake and physical exercise on the vertebral and femoral bone mineral density of children and adolescents. J Bone Miner Res **10:**675–682.
46. Johnston CCJ, Miller JZ, Slemenda CW, Reister TK, Hui S, Christian JC, Peacock M 1992 Calcium supplementation and increases in bone mineral density in children. N Engl J Med **327:**82–87.
47. Matkovic V, Fontana D, Tominac C, Goel P, Chestnut CH 1990 Factors that influence peak bone mass formation: A study of calcium balance and the inheritance of bone mass in adolescent females. Am J Clin Nutr **52:**878–888.
48. Bonjour JP, Carrie AL, Ferrari S, Clavien H, Slosman D, Theintz G, Rizzoli R 1997 Calcium-enriched foods and bone mass growth in prepubertal girls: A randomized, double-blind, placebo-controlled trial. J Clin Invest **99:**1287–1294.
49. Lehtonen-Veromaa MK, Mottonen TT, Nuotio IO, Irjala KM, Leino AE, Viikari JS 2002 Vitamin D and attainment of peak bone mass among peripubertal Finnish girls: A 3-y prospective study. Am J Clin Nutr **76:**1446–1453.
50. Specker B, Binkley T 2003 Randomized trial of physical activity and calcium supplementation on bone mineral content in 3- to 5-year-old children. J Bone Miner Res **18:**885–892.
51. Iuliano-Burns S, Saxon L, Naughton G, Gibbons K, Bass SL 2003 Regional specificity of exercise and calcium during skeletal growth in girls: A randomized controlled trial. J Bone Miner Res **18:**156–162.
52. Filaire E, Lac G 2002 Nutritional status and body composition of juvenile elite female gymnasts. J Sports Med Phys Fitness **42:**65–70.
53. Institute of Medicine 2002 Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein and Amino Acids. Food and Nutrition Board, National Academy Press, Washington, DC, USA.
54. Janz KF, Burns TL, Torner JC, Levy SM, Paulos R, Willing MC, Warren JJ 2001 Physical activity and bone measures in young children: The Iowa bone development study. Pediatrics **107:**1387–1393.
55. Morris FL, Naughton GA, Gibbs JL, Carlson JS, Wark JD 1997 Prospective ten-month exercise intervention in premenarcheal girls: Positive effects on bone and lean mass. J Bone Miner Res **12:**1453–1462.
56. Milliken G, Johnson D 2001 Analysis of Messy Data, Volume III: Analysis of Covariance. Chapman Hall/CRC Press, Boca Raton, FL, USA.
57. Baxter-Jones ADG, Maffulli N, Mirwald RL 2003 Does elite competition inhibit growth and delay in maturation in some gymnasts? Probably not. Pediatr Exerc Sci **15:**373–382.

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