Calcif Tissue Int (2002) 71:406–415
DOI: 10.1007/s00223-001-1105-z

Calcified
Tissue
International

Physical Activity Increases Bone Size in Prepubertal Boys and Bone Mass in Prepubertal Girls: A Combined Cross-Sectional and 3-Year Longitudinal Study

M. Sundberg,[1] P. Gärdsell,[2] O. Johnell,[2] M. K. Karlsson,[2] E. Ornstein,[1] B. Sandstedt,[1] I. Sernbo[2]

[1]Department of Orthopedics, Hässleholm-Kristianstad, Sweden
[2]Department of Orthopedics, Malmö University Hospital, Sweden

Received: 10 September 2001 / Accepted: 20 February 2002 / Online publication: 13 August 2002

Abstract. This study evaluates the effect on the skeleton of physical activity from age 9 to 16. In 42 girls and 44 boys, bone mass and bone size were evaluated longitudinally by dual-energy X-ray absorptiometry (DXA) from ages 13 to 16. Physical activity from ages 9 to 13 was cross-sectionally evaluated at baseline (age 13). Girls with high physical activity from ages 9 to 13 at baseline had higher femoral neck bone mineral content (FN BMC; g) ($P = 0.07$), higher FN areal bone mineral density (FN aBMD; g/cm^2), and higher FN volumetric BMD (FN vBMD; g/cm^3) (both $P < 0.05$) compared with girls of low activity. FN width (cm) and head aBMD (an unloaded region) showed no differences when comparing the two groups. Three years of further high and low activity (from ages 13 to 16) did not yield any increased differences between the two groups. Boys with high physical activity from ages 9 to 13, had at baseline higher FN BMC, FN aBMD, and FN width (all $P < 0.05$) compared with boys with low activity. FN vBMD and head aBMD showed no differences when comparing the two groups. Three years of further high and low activity did not yield any increased differences between the two groups. We conclude that exercise may yield skeletal benefits before age 13, and that 3 years of continued high or low level activity up to age 16 did not yield any increased differences in bone size or bone mass in either girls or boys.

Key words: Adolescents — Bone mineral density — Growth — Longitudinal — Physical activity

Increased peak bone mass and bone size could possibly reduce the prevalence of osteoporosis in old age. As peak bone mass is determined by both genetic and environmental factors [1–5], an increased level of physical activity could possibly increase peak bone mass and bone size. Data support this, indicating the skeleton to be most adaptable to physical activity before the completion of growth [6–8]. Higher bone mass has previously been reported in a cohort of 16-year-olds from a rural population compared with an urban cohort, more pronounced in boys than in girls, probably due to a more physically active lifestyle in the rural community [2]. Morris et al. [9] reported a positive skeletal effect after an 8-month training program in premenarcheal girls, and Bradney et al. [3] demonstrated an increased bone mass in prepubertal boys after an 8-month exercise program compared with controls. McKay et al. [10] found an increased bone mass in the trochanter region in prepubertal girls and boys after an 8-month training program compared with controls, whereas Blimkie et al. [11] and Witzke and Snow [12] reported no beneficial effects on the skeleton of exercise in pubertal girls after a 6- and 9-month training program, respectively. The studies cited evaluated mainly impact-loaded activity in volunteers. Whether an intervention program would result in a positive skeletal effect, including all children of school age (also less-motivated children), is unclear, even if McKay et al. [10] suggest this in their report of beneficial effects on the skeleton when a moderate exercise program in school physical education was implemented. Furthermore, the studies cited evaluated the intervention over a period of less than 1 year, and therefore, the question as to whether the results remain if the studies are extended over several years is unanswered.

The purpose of this combined cross-sectional and longitudinal study was to evaluate the effect of physical activity on bone mass accrual and bone size development during the pre- and peripubertal years. We hypothesized that a higher level of physical activity from ages 9 to 13 increases the bone modeling compared with a more sedentary lifestyle, and that additional high activity from ages 13 to 16 would further increase these differences. We posed the following questions: (1) whether from ages 9 to 13 more physically active children develop a higher bone mass and/or larger bone size

---

Correspondence to: Martin Sundberg, e-mail: Martin.Sundberg@skane.se

at age 13 than less active children, (2) whether continued high physical activity from ages 13 to 16 yields increased differences in bone mass and/or bone size.

Materials and Methods

All 13-year-old children, (45 girls, 48 boys) from a rural village in southern Sweden (Sösdala, population 2900), were invited to participate in this combined cross-sectional and longitudinal study. Bone mass and bone size were evaluated annually from ages 13 to 16. Seven of these children moved during the study period, leaving 86 children (44 boys and 42 girls) in the final database. Four measurements were performed, at which the attendance rate was 90–100%. All children underwent at least two consecutive measurements. For the calculations we included only individuals who had remained within the same activity group from ages 9 to 16 in the longitudinal analysis, namely, 36 girls and 36 boys.

Bone mass and bone size were evaluated by dual-energy X-ray absorptiometry (DXA) (Lunar DPX-L version 1.3z, Lunar, Madison, WI). Bone mineral content (BMC, g) and areal bone mineral density (aBMD, g/cm^2) were assessed for the total body (TB), the spine, and the femoral neck (FN), representing weight-loaded skeletal regions, and the head, representing an unloaded region. FN bone size (width, cm) and FN volumetric bone mineral density (vBMD, g/cm^3) were derived from the hip scan by the formula vBMD = BMC/estimated FN volume ($\pi \times r^2 \times$ FN length) where r = FN mid-diameter/2, assuming the FN to be cylindrical [13–15]. Total fat mass (kg) and total lean mass (kg) were derived from the total body scan. The precision evaluated by double measurements in 14 healthy individuals was for aBMD TB 0.4%, FN 1.6%, head 1.7%. The precision for FN volume was 1.7% and for FN vBMD 1.5%, for total fat mass 4.1% and total lean mass 0.6%. The long-term precision was 0.6% over the study period, evaluated by scanning a Hologic spine phantom. BMC and aBMD of the nondominant forearm were determined using single-energy X-ray absorptiometry (SXA) (Osteometer DTX-100, Osteometer, Denmark) in the distal radius (DR) and ulna where the distance between radius and ulna is 8 mm (cortical bone) and in the ultradistal radius (UDR) adjacent to the radiocarpal joint (trabecular bone). Bone mass in the calcaneus was evaluated by quantitative ultrasound (QUS) (Lunar Achilles+, Lunar, Madison, WI). This method is supposed to evaluate not only bone mass but also the quality of the skeleton and the skeletal architecture [16–19]. The mean value of broadband attenuation (BUA, dB/MHz), speed of sound (SOS, m/s) and Stiffness Index (SI) = ($0.67 \times$ BUA) + ($0.28 \times$ SOS) − 420) of the two heels are presented. The precision for BUA was 2.2%, for SOS 0.3%, and for SI 2.6%.

Height was measured by a standard height meter, and weight with a non-electrical scale. Segmental lengths (spine, arm, and leg) were measured with a ruler on the total body scan. The spine was measured from the chin to the last lumbar vertebra, the arm from the superior border of the humeral head to the wrist joint, and the leg from the superior border of the femoral head to the inferior border of the lateral malleolus. Pubertal stage was determined according to Tanner and assessed by self-grading, using photographs showing the different Tanner stages [20].

A questionnaire, evaluated in several other studies, registered lifestyle factors with special attention to physical activity [2, 8, 21, 22]. Dietary intake of calcium was not assessed since nutritional deficits are not a general problem in Sweden [23]. Socioeconomic and ethnic background as well as medical history, alcohol intake, smoking, and exercise were recorded. Based on a series of statements, corresponding to their own level of out-of-school activity, a score was created which took into account the seasonal variations in activity. In addition, hours per week spent in physical activity, type and duration of activity were recorded.

To evaluate the reliability of the physical activity reported in the questionnaire, we used the 20 m shuttle test [24] to determine maximal oxygen uptake. The test is described as being reliable in these age groups [25, 26]. VO_2max (ml/kg/min) was calculated by the formula developed by Léger et al. [26]:

$$VO_2\max = 31.025 + 3.238X - 3.248A + 0.1536XA$$

where X is speed and A is age. VO_2max was then related to the activity score and hours of exercise per week. VO_2max correlated with both the activity score ($r = 0.62$, $P < 0.001$) and the hours of exercise per week ($r = 0.75$, $P < 0.001$). The activity score correlated with hours of exercise per week ($r = 0.75$, $P < 0.001$). On the basis of this, which indicated the activity to be adequately reported in the questionnaire, we selected the activity score as the only measure of total activity level.

At the start of the study we evaluated retrospectively the activity level from 9 to 13 years by the questionnaire in order to determine the annual activity level over this period. An average activity level for the years proceeding age 13 (3.8 ± 2.4 years for the boys and 3.4 ± 2.1 years for the girls) was then calculated. On the basis of the activity score we divided the children into one high and one low activity group so that both groups had a similar number of children. A cross-sectional comparison of bone mass and bone size at age 13 was then performed between individuals in the high and the low activity group.

The skeletal effects of exercise from ages 13 to 16 were longitudinally evaluated by annual measurements. Activity level was recorded at every visit and an average activity score for the period was calculated by adding the activity scores from each measurement divided by the number of measurements. Based on this activity score, the children were divided into one low and one high activity group, once more with a comparable number of children in the two groups. When comparing the activity levels from ages 9 to 13 with the activity levels from ages 13 to 16, 19% of the boys and 14% of the girls changed activity group from the first to the second period. To be able to evaluate the effect of an additional 3 years of high activity from ages 13 to 16, we included only individuals who had remained within the same activity group from ages 9 to 16 in the longitudinal analysis, namely, 36 girls and 36 boys.

As part of the school curriculum all children had physical education 2 × 40 min per week from ages 9 to 13 and 4 × 40 min per week from ages 13 to 16. During their leisure time, 11 of the 36 girls (2 soccer, 1 orienteering, 6 horseback riding, 2 swimming) and 20 of the 36 boys (16 soccer, 2 motorcross, 1 ice-hockey, 1 swimming) were taking exercise at least twice a week at a sports club from the ages of 9 to 13. Fifteen girls (5 soccer, 1 track and field, 8 horseback riding, 1 swimming) and 17 boys (8 soccer, 1 floreball, 2 fitness center, 1 tennis, 1 wrestling, 1 orienteering, 1 judo, 1 motorcross) were exercising at least twice a week at a sports club from ages 13 to 16. Prior to the start of the study (which was approved by the Ethics Committee of the University of Lund) the school, the children, and their parents signed a letter of consent to participate.

Statistical calculations were done using Statistica version 5.1 (StatSoft). Spearman's rank test was used for the correlations. Student's t-test between means was used for group comparisons. ANCOVA was used when adjusting for differences in weight, height, and Tanner stage. ANOVA was used to compare the development of bone mass and bone size in relation to age and when the slopes in the high and low activity groups over age were compared (test of parallelism between slopes).

Results

Girls

Girls with a high activity level from ages 9 to 13 had, at age 13, higher FN BMC ($P = 0.07$), FN aBMD, FN vBMD, and calcaneus QUS (all $P < 0.05$) compared

Table 1. Cross-sectional data at age 13 in girls and boys. Activity from age 9 to 13 was retrospectively evaluated

	Girls				Boys			
	Low $n = 21$	High $n = 21$	*P*	*P* adj	Low $n = 21$	High $n = 21$	*P*	*P* adj
Age, years	13.2 ± 0.3	13.2 ± 0.4	0.7	—	13.2 ± 0.3	13.3 ± 0.2	0.5	—
Height, cm	157.3 ± 7	160.5 ± 5.6	0.1	—	159.4 ± 6.9	160.0 ± 8.4	0.8	—
Weight, kg	49.4 ± 9.3	50.7 ± 8.9	0.6	—	50.1 ± 10.3	48.8 ± 6.6	0.6	—
Total fat mass, kg	13.1 ± 6.8	12 ± 6.9	0.6	0.2	10.1 ± 5.1	8.4 ± 4.6	0.3	0.3
Total lean mass, kg	33.2 ± 4.4	35.7 ± 3.9	0.07	0.3	37.0 ± 6.3	37.1 ± 6.1	0.9	0.5
Segmental length, cm								
Spine	46.5 ± 2.9	47.5 ± 3.0	0.3	0.7	45.6 ± 2.9	45.5 ± 3.1	0.9	0.9
Arm	50.3 ± 3.7	51.1 ± 1.9	0.3	0.6	50.8 ± 3.0	51.4 ± 3.7	0.5	0.7
Leg	79.0 ± 4.8	79.4 ± 4.2	0.8	0.1	80.7 ± 4.0	80.2 ± 5.6	0.7	0.1
Skeletal width, cm								
Femoral neck	2.90 ± 0.28	2.94 ± 0.21	0.6	0.5	2.95 ± 0.4	3.2 ± 0.34	0.03	0.005
BMC, g								
Total body	1953 ± 421	2102 ± 390	0.2	0.5	2007 ± 473	2064 ± 381	0.7	0.05
Spine	194 ± 52	208 ± 48	0.3	0.8	185 ± 53	179 ± 41	0.7	0.7
Femoral neck	3.86 ± 0.8	4.30 ± 0.69	0.07	0.2	4.30 ± 0.98	5.11 ± 0.94	0.009	< 0.001
Distal radius	2.13 ± 0.43	2.30 ± 0.48	0.2	0.5	2.34 ± 0.49	2.31 ± 0.37	0.8	0.8
Ultradistal radius	0.95 ± 0.26	1.16 ± 0.32	0.02	0.1	1.40 ± 0.5	1.25 ± 0.35	0.3	0.4
aBMD, g/cm^2								
Total body	1.02 ± 0.10	1.04 ± 0.10	0.7	0.9	1.00 ± 0.09	1.04 ± 0.08	0.2	0.003
Spine	0.96 ± 0.15	0.98 ± 0.13	0.7	0.8	0.90 ± 0.11	0.95 ± 0.10	0.2	0.002
Femoral neck	0.88 ± 0.12	0.97 ± 0.12	0.02	0.07	0.96 ± 0.13	1.06 ± 0.12	0.02	0.004
Head	1.91 ± 0.23	1.86 ± 0.25	0.6	0.4	1.79 ± 0.19	1.82 ± 0.13	0.6	0.2
Distal radius	0.33 ± 0.05	0.34 ± 0.05	0.5	0.7	0.36 ± 0.05	0.35 ± 0.04	0.7	0.7
Ultradistal radius	0.31 ± 0.05	0.33 ± 0.06	0.1	0.2	0.35 ± 0.07	0.34 ± 0.05	0.7	0.7
vBMD, g/cm^3								
Femoral neck	0.39 ± 0.05	0.42 ± 0.05	0.03	0.04	0.42 ± 0.06	0.42 ± 0.05	0.9	0.6
QUS								
BUA, dB/MHz	105.1 ± 7.3	112.5 ± 10.7	0.01	0.02	107.2 ± 9.8	112.1 ± 8.6	0.1	0.049
SOS, m/s	1546 ± 25.9	1561 ± 32.4	0.1	0.1	1544 ± 24	1560 ± 24	0.03	0.03
Stiffness index	82.8 ± 10.8	92 ± 15.4	0.03	0.05	83.7 ± 12	91.3 ± 11.6	0.04	0.03

The children were divided into two groups (high and low) depending on reported physical activity level between ages 9 to 13 in order to achieve comparative numbers of children in each group. Unadjusted comparisons (*P*) and comparisons adjusted for height, weight, and Tanner stage (*P* adj) are presented. Values are the mean ± SD

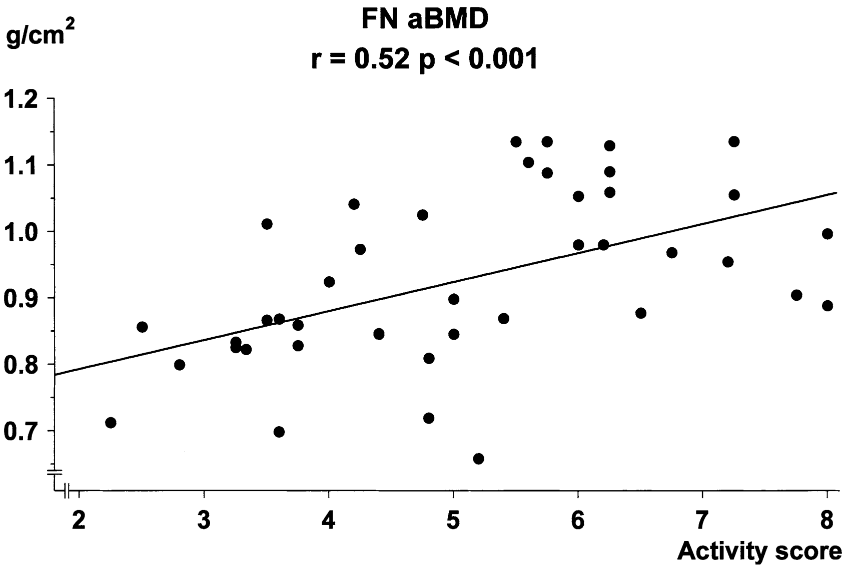

Fig. 1. Dose-response curve for femoral neck areal HMD (FNaBMD; g/cm^3) at age 13 and activity score from ages 9 to 16 for girls.

Table 2. Longitudinal data in girls from ages 13 to 16

	Data at age 13				Data at age 16				3-year longitudinal change			
	Low $n = 18$	High $n = 18$	P	P adj	Low $n = 17$	High $n = 17$	P	P adj	Low $n = 18$	High $n = 18$	P	P adj
Age, years	13.1 ± 0.3	13.2 ± 0.4	0.5	—	15.9 ± 0.3	16.0 ± 0.4	0.5	—	2.8 ± 0.01	2.8 ± 0.01	0.7	—
Height, cm	157.2 ± 6.8	160.5 ± 5.7	0.1	—	164.5 ± 7.8	165.6 ± 5.9	0.7	—	7.7 ± 5.1	5.3 ± 3.4	0.1	—
Weight, kg	47.3 ± 7.1	51.6 ± 9.3	0.1	—	55.8 ± 7.5	58.4 ± 11.5	0.4	—	9.1 ± 5.0	7.1 ± 7.5	0.4	—
Total fat mass, kg	11.6 ± 5.6	12.1 ± 7.5	0.8	0.048	16.2 ± 7.5	15.2 ± 9.7	0.8	0.1	4.8 ± 3.8	3.4 ± 6.0	0.4	0.2
Total lean mass, kg	32.7 ± 3.8	36.3 ± 3.6	0.006	0.07	36.7 ± 3.5	40.6 ± 3.4	0.002	0.009	4.3 ± 3.3	4.3 ± 2.7	1	0.005
Segmental length, cm												
Spine	46.4 ± 2.6	47.8 ± 3.0	0.2	0.9	49.6 ± 3.1	50.6 ± 2.4	0.3	0.6	3.1 ± 2.9	2.8 ± 2.2	0.7	0.04
Arm	50.5 ± 3.6	51.1 ± 1.9	0.5	0.5	52.5 ± 3.9	52.5 ± 2.4	1	0.6	2.2 ± 1.6	1.6 ± 1.5	0.3	0.8
Leg	79.1 ± 4.8	78.9 ± 4.0	0.9	0.02	82.0 ± 5.4	80.6 ± 3.7	0.4	0.1	3.1 ± 2.7	2.0 ± 2.0	0.2	0.9
Skeletal width, cm												
Femoral neck	2.89 ± 0.23	2.96 ± 0.21	0.4	0.6	3.23 ± 0.30	3.17 ± 0.23	0.6	0.4	0.36 ± 0.28	0.23 ± 0.27	0.2	0.7
BMC, g												
Total body	1875 ± 299	2159 ± 390	0.02	0.1	2385 ± 237	2541 ± 358	0.1	0.5	541 ± 226	403 ± 248	0.1	0.4
Spine	187 ± 41	215 ± 48	0.06	0.5	249 ± 35	260 ± 45	0.4	0.8	65.1 ± 37.7	45.6 ± 36.7	0.1	0.7
Femoral neck	3.78 ± 0.57	4.45 ± 0.60	0.002	0.02	4.78 ± 0.64	5.08 ± 0.66	0.2	0.2	1.06 ± 0.71	0.66 ± 0.67	0.1	0.5
Distal radius	2.11 ± 0.39	2.39 ± 0.45	0.05	0.2	2.67 ± 0.31	2.96 ± 0.40	0.02	0.1	0.60 ± 0.20	0.58 ± 0.15	0.8	0.5
Ultradistal radius	0.93 ± 0.27	1.19 ± 0.33	0.02	0.1	1.35 ± 0.34	1.55 ± 0.36	0.1	0.3	0.45 ± 0.37	0.38 ± 0.25	0.6	0.5
aBMD, g/cm^2												
Total body	1.01 ± 0.08	1.05 ± 0.09	0.1	0.4	1.12 ± 0.06	1.15 ± 0.09	0.4	0.5	0.12 ± 0.04	0.10 ± 0.05	0.1	0.6
Spine	0.93 ± 0.10	1.00 ± 0.13	0.1	0.4	1.15 ± 0.13	1.17 ± 0.15	0.7	1	0.22 ± 0.12	0.17 ± 0.12	0.2	0.2
Femoral neck	0.87 ± 0.09	1.00 ± 0.10	< 0.001	0.002	0.99 ± 0.10	1.07 ± 0.13	0.06	0.05	0.12 ± 0.10	0.07 ± 0.09	0.1	0.4
Head	1.87 ± 0.19	1.87 ± 0.27	1	0.5	2.19 ± 0.21	2.14 ± 0.27	0.5	0.2	0.33 ± 0.12	0.27 ± 0.10	0.1	0.2
Distal radius	0.33 ± 0.04	0.35 ± 0.05	0.2	0.3	0.41 ± 0.04	0.43 ± 0.04	0.2	0.4	0.08 ± 0.03	0.07 ± 0.02	0.8	0.9
Ultradistal radius	0.30 ± 0.05	0.34 ± 0.05	0.02	0.1	0.35 ± 0.04	0.37 ± 0.05	0.2	0.4	0.05 ± 0.03	0.026 ± 0.03	0.03	0.1
vBMD, g/cm^3												
Femoral neck	0.38 ± 0.04	0.43 ± 0.04	0.003	0.004	0.39 ± 0.06	0.43 ± 0.07	0.1	0.08	0.007 ± 0.04	−0.002 ± 0.04	0.6	0.6
QUS												
BUA, dB/MHz	105.3 ± 7.6	114 ± 10.2	0.007	0.03	117.0 ± 6.2	120.4 ± 8.5	0.2	0.3	12.8 ± 8.1	6.2 ± 9.7	0.04	0.1
SOS, m/s	1545 ± 24	1569 ± 26	0.009	0.01	1579 ± 22	1600 ± 23	0.009	0.003	35.6 ± 18.2	28.9 ± 14.7	0.3	0.4
Stiffness index	82.8 ± 11.0	95.2 ± 13.3	0.004	0.01	99.8 ± 8.2	108.1 ± 9.6	0.01	0.009	18.4 ± 9.0	12.2 ± 9.8	0.07	0.2

The girls were divided into two groups (high and low) depending on reported physical activity level between the age of 9 and 16, in order to achieve comparative numbers of girls in each group. Only girls who did not change their activity level between the ages of 9 and 16 are included. Unadjusted comparisons (P) and comparisons adjusted for height, weight, and Tanner stage (P adj) are presented. Values are the mean ± SD

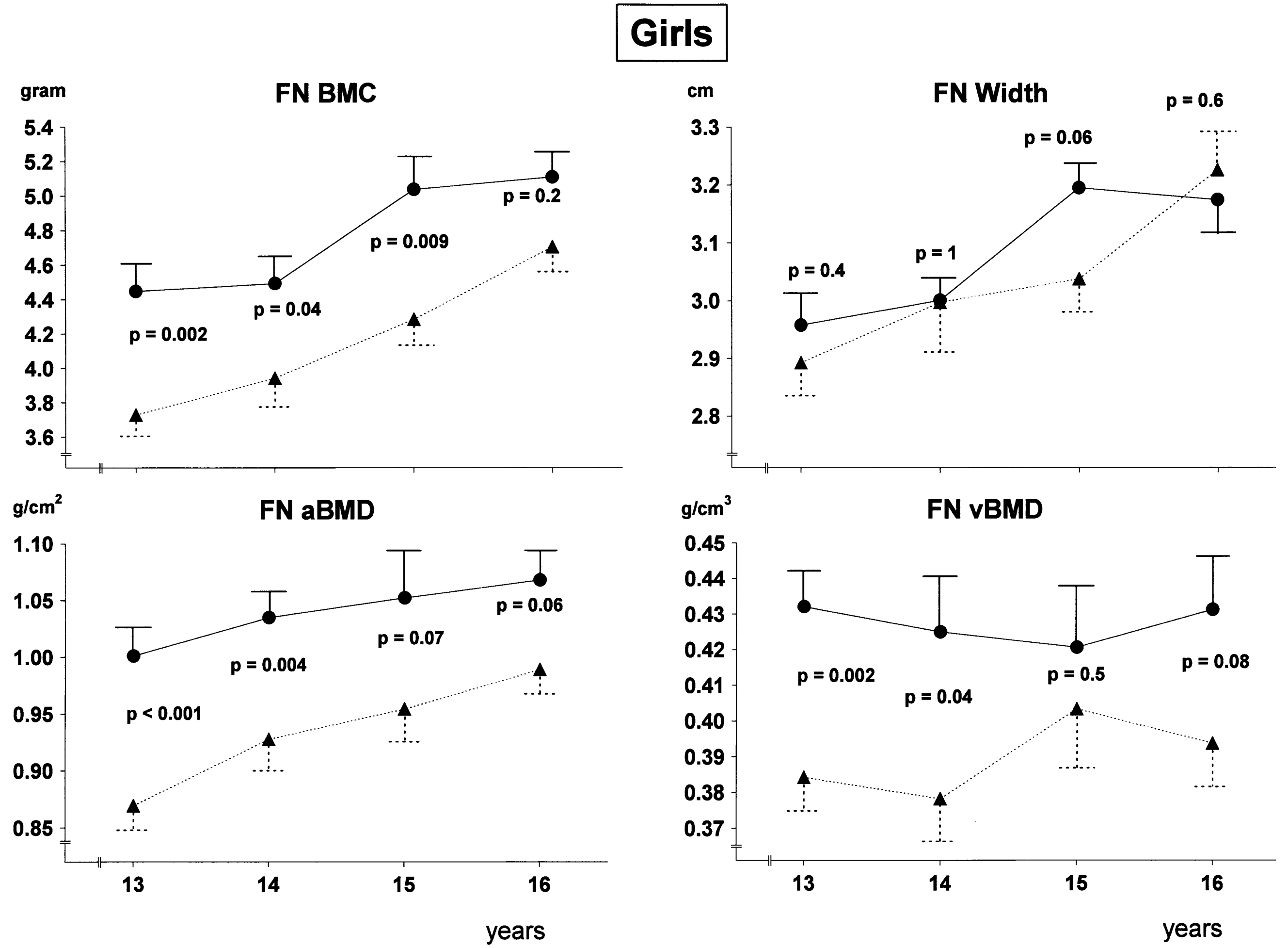

Fig. 2. Longitudinal annual data from ages 13 to 16, presented as mean ± SEM for bone mineral content (BMC; g), bone size (width; cm), areal bone mineral density (aBMD; g/cm^2), and volumetric bone mineral density (vBMD; g/cm^3) in the femoral neck (FN) in girls with high (●) and low (▲) activity level from ages 9 to 16. Only girls who did not change their activity level between ages 9 to 16 are included. *p*-values represent comparisons between high and low activity groups each year.

with girls with a low activity level. FN width and head aBMD showed no differences in the comparison between the two groups (Table 1). FN aBMD at age 13 and an activity score of 9–16 are presented in Figure 1.

Three years of additional high and low activity (from ages 13 to 16) did not show any increased differences when the two groups were compared, and the changes in bone mass and bone size (adjusted for changes in height, weight, and Tanner stage) showed no differences in a comparison between the high and the low activity groups (Table 2, Fig. 2).

FN BMC, FN aBMD, and FN width all increased with age in both the low and high activity groups (all $P < 0.01$) but FN vBMD did not, in either of the two groups (both $P > 0.6$). No significant differences were found when the slopes of FN BMC, FN aBMD, FN width, and FN vBMD were compared over age, either in the high or low activity groups (all comparisons between the slopes $P > 0.3$) (Fig. 2).

The data on development with age (longitudinal data) include only girls who did not change activity level from ages 9 to 16 (86% of all girls measured) (Table 2, Fig. 2). No differences were found when comparing girls with a high and those with a low activity level, either at age 13 or at age 16, regarding age at menarche, Tanner stage, parents' occupation and education, type of housing, intake of dairy products, consumption of alcohol, and smoking.

The pubertal development ranged from median Tanner 3 (range 1–5) at age 13 to median Tanner 4 (range 4–5) at age 16.

Boys

Boys with a high activity level from ages 9 to 13 had, at age 13, higher FN BMC, FN aBMD, calcaneus QUS, and FN width (all $P < 0.05$) than boys with a low ac-

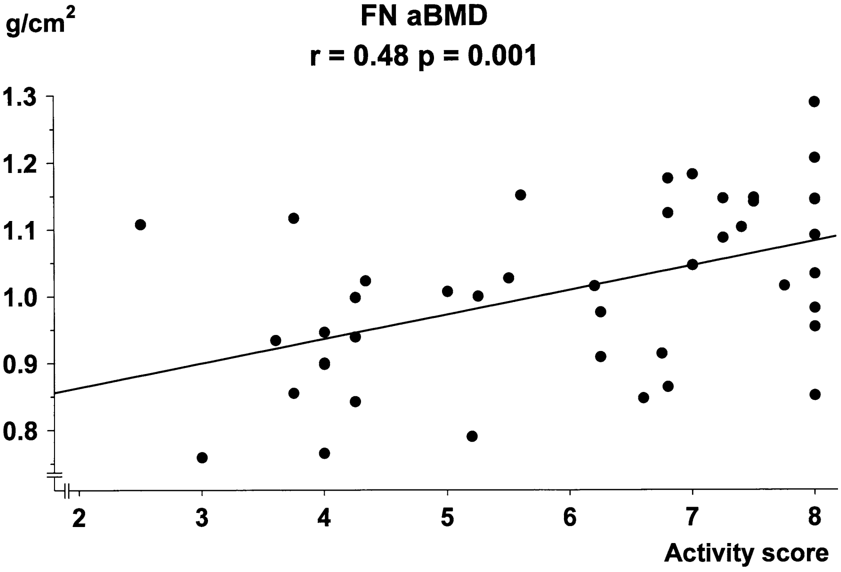

Fig. 3. Dose-response curve for femoral neck areal BMD (FNaBMD; g/cm^3) at age 13 and activity score from ages 9 to 16 for boys.

tivity level. FN vBMD and head aBMD (an unloaded region) showed no differences when the two groups were compared (Table 1). FN aBMD at age 13 and activity score 9–16 are presented in Figure 3.

Three years of additional high and low activity level (from ages 13 to 16) showed no increased differences when comparing the two activity groups, and the changes in bone mass and bone size (adjusted for changes in height, weight, and Tanner stage) showed no differences when the high and low activity groups were compared (Table 3 and Fig. 4).

FN BMC, FN aBMD and FN width all increased with age in both the low and high activity groups (all $P < 0.002$) while FN vBMD did not in either of the two groups (in both $P > 0.8$). No significant differences were found when comparing the slopes of FN BMC, FN aBMD, and FN vBMD in relation to increasing age, either in the high or low activity group (all comparisons between the slopes $P > 0.3$). There was a tendency towards a larger increase in FN width in the boys of the low activity group than in those in the high activity group from ages 13 to 16 ($P = 0.09$ when the slopes were compared) (Fig. 4). The mean increase in FN width was higher in the less active than in the more active boys between ages 13 and 16 ($P = 0.04$) but after adjusting for changes in height, weight, and Tanner stage no difference remained ($P = 0.2$) (Table 3).

The data on development with age (longitudinal data) include only boys who did not change activity level from ages 9 to 16 (81% of all boys measured) (Table 3 and Fig. 4). No differences were found when comparing boys with high and low activity level either at ages 13 or 16 regarding Tanner stage, parents' occupation and education, type of housing, intake of dairy products, or alcohol consumption. During the period between 13 to 16, smoking was more common in the high activity group than in the low activity group ($P = 0.04$). No such difference was found over the period 9 to 13 years.

The pubertal development ranged from median Tanner 3 (range 1–5) at age 13 to median Tanner 4 (range 4–5) at age 16.

Discussion

This study supports earlier reports that bone modeling is modifiable by physical activity during the prepubertal years [27]. However, since the evaluation at age 13 in the present study is cross-sectional, as the children were not randomized into high and low exercise levels and as differences were already found at age 13, we cannot exclude sampling bias to be the explanation of the differences. It seems probable that bigger and stronger children or more mature and developed children are more successful at sports than their smaller and less mature counterparts, and thus possibly choose to participate in exercise to a higher extent. However, neither height, weight, total muscle mass (lean mass), nor total fat mass showed any differences in a comparison between the highly active and the less active individuals. Even if these traits did not show any differences, maybe a bigger or denser skeleton could be a selection criterion for individuals subjected to exercise. This is also not very plausible, as the head aBMD, a region virtually unloaded during exercise [28, 29], showed no difference in the comparison between the two groups. Maybe more mature individuals chose to participate in physical activity. This also does not seem very plausible as there were no significant differences in Tanner stages at age 13 or at age 16 between the activity groups, in either boys or girls. After adjustment for differences in height, weight and Tanner stages, all results remained. Fur-

Table 3. Longitudinal data in boys from ages 13 to 16

	Data at age 13				Data at age 16				3-year longitudinal change			
	Low $n=17$	High $n=18$	*P*	*P* adj	Low $n=14$	High $n=17$	*P*	*P* adj	Low $n=14$	High $n=17$	*P*	*P* adj
Age, years	13.3 ± 0.3	13.3 ± 0.2	0.8	—	16.0 ± 0.3	16.0 ± 0.2	1	—	2.8 ± 0.01	2.7 ± 0.01	0.1308	—
Height, cm	159.4 ± 6.9	159.9 ± 7.8	0.8	—	176.2 ± 5.9	175.8 ± 6.8	0.9	—	16.3 ± 4.3	16.1 ± 5.8	0.9	—
Weight, kg	50.0 ± 10.2	49.3 ± 6.5	0.8	—	64.8 ± 10.2	65.6 ± 7.7	0.8	—	14.4 ± 6.6	16.5 ± 4.9	0.3	—
Total fat mass, kg	9.7 ± 4.9	8.5 ± 5.0	0.5	0.4	9.1 ± 4.0	9.6 ± 5.7	0.8	0.5	–0.5 ± 3.9	1.5 ± 2.5	0.1	0.8
Total lean mass, kg	37.2 ± 6.5	37.6 ± 6.1	0.9	0.5	51.8 ± 6.4	52.1 ± 5.5	0.9	0.5	14.0 ± 4.0	14.4 ± 4.1	0.8	0.7
Segmental length, cm												
Spine	45.4 ± 2.8	45.8 ± 3.2	0.7	0.5	54.1 ± 2.4	53.2 ± 3.1	0.4	0.3	8.3 ± 2.5	7.2 ± 2.7	0.3	0.1
Arm	51.1 ± 3.2	51.2 ± 3.5	0.9	0.9	57.3 ± 2.8	57.1 ± 3.7	0.9	0.6	6.1 ± 2.6	5.9 ± 1.9	0.8	0.8
Leg	80.8 ± 4.0	79.9 ± 4.7	0.6	0.1	87.9 ± 3.8	86.8 ± 4.1	0.4	0.2	7.1 ± 2.1	7.1 ± 3.4	1	0.7
Skeletal width, cm												
Femoral neck	2.95 ± 0.43	3.21 ± 0.34	0.05	0.004	3.67 ± 0.25	3.68 ± 0.33	1	0.6	0.7 ± 0.30	0.47 ± 0.28	0.04	0.2
BMC, g												
Total body	1990 ± 473	2114 ± 368	0.4	0.02	2944 ± 500	3120 ± 407	0.3	0.04	926 ± 258	985 ± 224	0.5	0.5
Spine	183 ± 50.3	183 ± 40.1	1	0.4	294 ± 60.7	307 ± 44.4	0.5	0.2	112 ± 38.5	122.4 ± 29.3	0.4	0.8
Femoral neck	4.25 ± 0.98	5.23 ± 0.90	0.004	< 0.001	6.31 ± 0.98	6.92 ± 1.02	0.1	0.03	1.97 ± 0.79	1.66 ± 0.99	0.4	0.7
Distal radius	2.36 ± 0.52	2.36 ± 0.38	1	0.8	3.49 ± 0.69	3.44 ± 0.59	0.8	0.9	1.12 ± 0.21	1.05 ± 0.28	0.5	0.9
Ultradistal radius	1.39 ± 0.52	1.28 ± 0.36	0.4	0.5	2.00 ± 0.61	1.88 ± 0.52	0.6	0.7	0.59 ± 0.39	0.57 ± 0.34	0.8	0.3
aBMD, g/cm^2												
Total body	1.00 ± 0.09	1.06 ± 0.07	0.045	< 0.001	1.17 ± 0.09	1.23 ± 0.08	0.08	0.004	0.17 ± 0,05	0.17 ± 0.04	0.9	0.9
Spine	0.90 ±0.11	0.97 ± 0.09	0.06	0.002	1.14 ± 0.18	1.15 ± 0.11	0.8	0.5	0.25 ± 0.13	0.18 ± 0.12	0.08	0.5
Femoral neck	0.95 ± 0.12	1.08 ± 0.11	0.002	< 0.001	1.15 ± 0.16	1.25 ± 0.14	0.05	0.04	0.18 ± 0.12	0.16 ± 0.13	0.8	0.3
Head	1.80 ± 0.19	1.85 ± 0.12	0.4	0.2	2.00 ± 0.23	2.01 ± 0.15	1	0.6	0.20 ± 0.10	0.15 ± 0.11	0.3	0.3
Distal radius	0.36 ± 0.05	0.36 ± 0.03	1	0.6	0.46 ± 0,05	0.46 ± 0.06	0.9	0.7	0.10 ± 0.009	0.10 ± 0.04	0.5	0.8
Ultradistal radius	0.35 ± 0.07	0.35 ± 0.05	1	0.6	0.43 ± 0.08	0.44 ± 0.06	0.8	0.5	0.08 ± 0.03	0.08 ± 0.04	0.9	0.7
vBMD, g/cm^3												
Femoral neck	0.42 ± 0.06	0.43 ± 0.05	0.4	0.4	0.40 ± 0.06	0.44 ± 0.06	0.09	0.1	–0.02 ± 0.05	0.002 ± 0.04	0.2	0.2
QUS												
PBUA, dB/MHz	107.0 ± 10.4	112.9 ± 8.8	0.1	0.04	125.1 ± 8.9	128.2 ± 7.2	0.3	0.4	18.2 ± 10.9	16.7 ± 6.2	0.7	1
SOS, m/s	1543 ± 23	1564 ± 24	0.02	0.02	1599 ± 39	1611 ± 30	0.4	0.4	56.4 ± 29.5	46.7 ± 25.8	0.4	1
Stiffness index	83.3 ± 12.3	92.9 ± 11.6	0.02	0.02	110.8 ± 14.4	116.4 ± 11.5	0.3	0.3	27.8 ± 12.7	24.1 ± 9.0	0.4	1

The boys were divided into two groups (high and low) depending on reported physical activity level between the age of 9 and 16, in order to achieve comparative numbers of boys in each group. Only boys who did not change their activity level between the ages of 9 and 16 are included. Unadjusted and comparisons (*P*) and comparisons adjusted for height, weight, and Tanner stage (*P* adj) are presented. Values are the mean ± SD

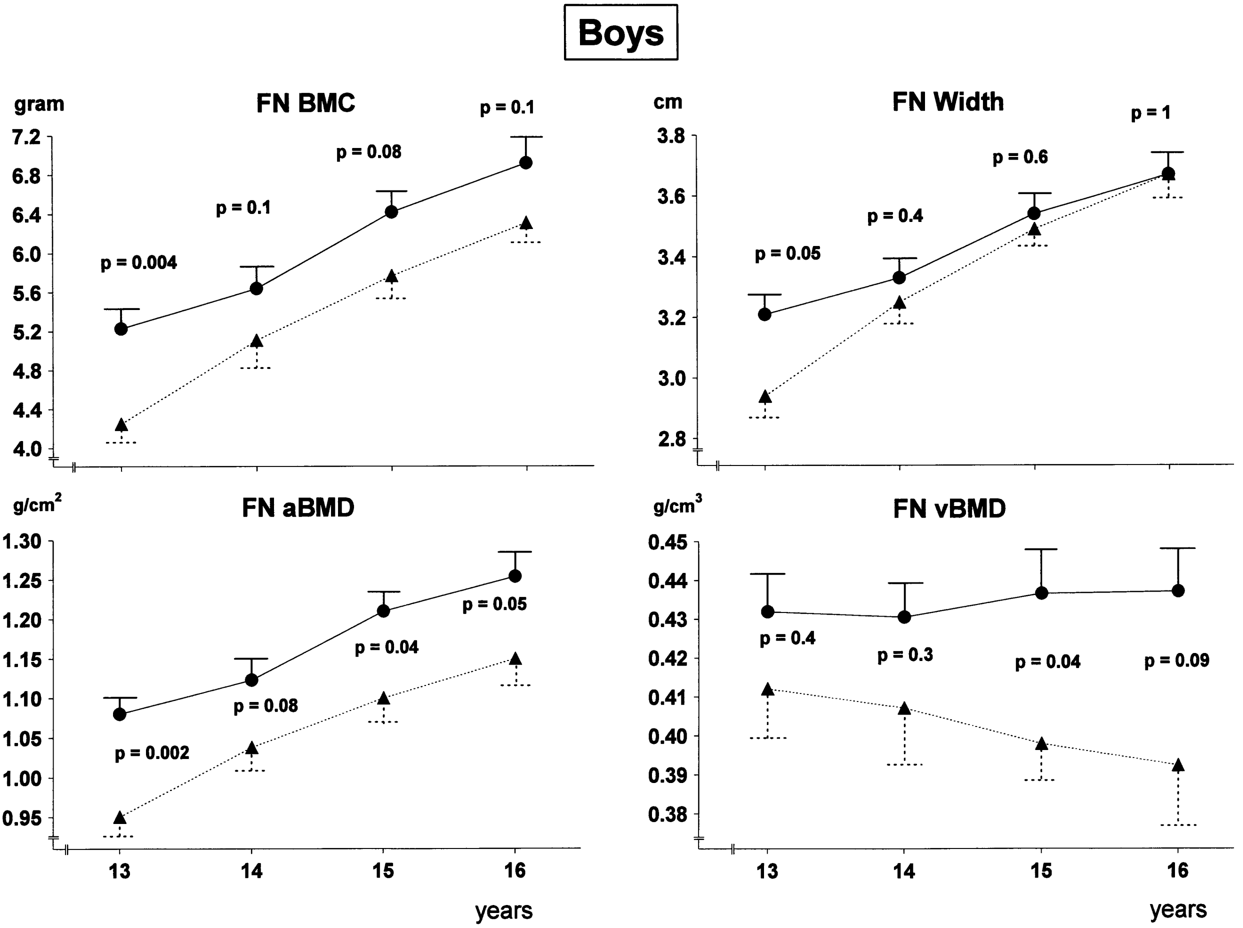

Fig. 4. Longitudinal annual data from ages 13 to 16, presented as mean ± SEM for bone mineral content (BMC; g), bone size (width; cm), areal bone mineral density (aBMD; g/cm^2), and volumetric bone mineral density (vBMD; g/cm^3) of the femoral neck (FN) in boys with high (●) and low (▲) activity level from ages 9 to 16. Only boys who did not change their activity level between ages 9 to 16 are included. *p*-values represent comparisons between high and low activity groups each year.

thermore, the dose-response curves for physical activity and FN aBMD at age 13 support an exercise-induced skeletal response. It seems that the most probable explanation of the described skeletal differences at age 13 was the difference in activity levels during the years preceding the measurements. The present data also support previous reports indicating the skeleton to be more influenced by physical activity pre- than peri- and postpubertal [3, 11, 12, 30–32].

Since the evaluation at age 13 was cross-sectional, we cannot determine at what age increased bone modeling could first be registered. Furthermore, if skeletal benefits could already be achieved before the age of 9, it is unclear whether these benefits could be enhanced with continued high activity from ages 9 to 13. The literature reports Tanner stages 2 to 3 to be the period when exercise may enhance bone modeling [33]. Kannus et al. [27] reported for female squash and tennis players, that the starting age of activity is of importance, when the aBMD of the dominant arm was related to this.

Three years of additional high activity in individuals with a high activity level from ages 9 to 13 did not show increased bone size or bone mass differences compared with the less active children, in either girls or boys. Since the sample sizes were too small for subgroup analyses, we cannot evaluate whether at age 13 sedentary children, who increase their activity level during the following 3 years, could achieve an increase in bone size and/or bone mass compared with children with a continued sedentary lifestyle. Neither can we evaluate whether children with high activity at age 13, who reduced their activity level during the following 3 years, retain the beneficial skeletal effects achieved during the years preceding age 13. However, there are some data in the literature indicating that sedentary children who increase their activity level during the peripubertal years may increase bone modeling, as seen to some extent in boys [8].

The purpose of this study was to evaluate differences in activity level on a scale that is realistic for most children, and not to evaluate competitive exercises.

Also, many sports activities performed during leisure time, such as swimming and horseback riding, may be insufficient in load to produce a skeletal response. Greater differences and involving impact-loaded activities could possibly produce differences in skeletal development, also during the period 13 to 16 years. It may be that the type of activity and the magnitude of the difference in activity level presented in this study was too small to produce a difference in skeletal development. However, previous reports suggest that also with intense training it is difficult to achieve exercise-induced skeletal benefits during adolescence [12, 31].

Exercise is often reported to increase periosteal apposition in bone (building a bigger bone) because this surface is exposed to the greatest mechanical stress [34], but also the endocortical contraction may contribute to increased cortical width. Increased bone size (a larger but not denser bone) at age 13 in more active boys indicates a periosteal response during the years preceding age 13. As the difference in bone size between more and less active boys was not longer apparent at age 16, and as there was a tendency of higher vBMD in active boys, this could indicate endocortical contraction adding bone strength at this age. Wittich et al. [35] reported, for professional male soccer players, that leg bone size was 5% larger in soccer players than in controls and Haapasalo et al. [36] reported that former elite male tennis players (age 30 years), had a bigger but not a denser skeleton (vBMD). The discrepancies between the present data and cited studies could be due to the different activity levels and the different skeletal regions measured.

In contrast, vBMD was higher at age 13 in the more active girls than in the less active girls. This suggests increased endosteal apposition to be the result of exercise during this period, with no changes in the relation occurring with an additional 3 years of high and low activity.

DXA is supposed to measure quantitative bone mass, whereas QUS is supposed to measure a different skeletal property, maybe architecture [16–18, 37]. The exercise-induced QUS benefits reported in this study suggest that exercise may confer beneficial effects not only in bone mass but also in other skeletal properties important for skeletal strength. Daly et al. [38] support this when reporting higher QUS values in pre- and peripubertal male gymnasts compared with controls.

In summary, we can state that increased physical activity may influence bone modeling before age 13 in both genders. Three years of additional high activity did not increase these differences even if the relative contribution of bone mass and bone size may change in boys. The efforts by the community to enhance the skeletal strength in the general population, by means of increased physical activity, should probably be initiated before age 13.

Acknowledgments. Financial support was obtained from Kristianstad Higher Educational School, Region Skåne, Lund University, and Malmö University Hospital Foundations.

References

1. Slemenda CW, Miller JZ, Hui SL, Reister TK, Johnston Jr CC (1991) Role of physical activity in the development of skeletal mass in children. J Bone Miner Res 6:1227–1233
2. Sundberg M, Düppe H, Gärdsell P, Johnell O, Ornstein E, Sernbo I (1997) Bone mineral density in adolescents. Higher values in a rural area—a population-based study of 246 subjects in southern Sweden. Acta Orthop Scand 68:456–460
3. Bradney M, Pearce G, Naughton G, Sullivan C, Bass S, Beck T, Carlson J, Seeman E (1998) Moderate exercise during growth in prepubertal boys: changes in bone mass, size, volumetric density, and bone strength. A controlled prospective study. J Bone Miner Res 13:1814–1821
4. Valdimarsson Ö, Kristinsson JÖ, Stefansson SÖ, Valdimarsson S, Sigurdsson G (1999) Lean mass and physical activity as predictors of bone mineral density in 16–20-year-old women. J Intern Med 245:489–496
5. Bailey DA, McKay HA, Mirwald RL, Crocker PR, Faulkner RA (1999) A six-year longitudinal study of the relationship of physical activity to bone mineral accrual in growing children: the University of Saskatchewan bone mineral accrual study. J Bone Miner Res 14:1672–1679
6. Bailey DA (1997) The Saskatchewan Pediatric Bone Mineral Accrual Study: bone mineral acquisition during the growing years. Int J Sports Med 18(suppl 3):S191–S194
7. McKay HA, Bailey DA, Mirwald RL, Davison KS, Faulkner RA (1998) Peak bone mineral accrual and age at menarche in adolescent girls: a 6-year longitudinal study. J Pediatr 133:682–687
8. Sundberg M, Gärdsell P, Johnell O, Karlsson MK, Ornstein E, Sandstedt B, Sernbo I (2001) Peripubertal moderate exercise increases bone mass in boys but not in girls: a population-based intervention study. Osteoporos Int 12:230–238
9. 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
10. 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
11. Blimkie CJ, Rice S, Webber CE, Martin J, Levy D, Gordon CL (1996) Effects of resistance training on bone mineral content and density in adolescent females. Can J Physiol Pharmacol 74:1025–1033
12. Witzke KA, Snow CM (2000) Effects of plyometric jump training on bone mass in adolescent girls. Med Sci Sports Exerc 32:1051–1057
13. Cowell CT, Lu PW, Lloyd-Jones SA, Briody JN, Allen JR, Humphries IR, Reed E, Knight J, Howman-Giles R, Gaskin K (1995) Volumetric bone mineral density–a potential role in paediatrics. Acta Paediatr (supp1)411:6–12,17
14. Lu PW, Cowell CT, Lloyd-Jones SA, Briody JN, Howman-Giles R (1996) Volumetric bone mineral density in normal subjects, aged 5–27 years. J Clin Endocrinol Metab 81:1586–1590
15. Seeman E, Duan Y, Fong C, Edmonds J (2001) Fracture site-specific deficits in bone size and volumetric density in men with spine or hip fractures. J Bone Miner Res 16:120–127
16. Hans D, Schott AM, Meunier PJ (1993) Ultrasonic assessment of bone: a review. Eur J Med 2:157–163

17. Glüer CC, Wu CY, Jergas M, Goldstein SA, Genant HK (1994) Three quantitative ultrasound parameters reflect bone structure. Calcif Tissue Int 55:46–52
18. Karlsson MK, Obrant KJ, Nilsson BE, Johnell O (1998) Bone mineral density assessed by quantitative ultrasound and dual energy X-ray absorptiometry. Normative data in Malmo, Sweden. Acta Orthop Scand 69:189–193
19. Karlsson M, Duan Y, Ahlborg H, Obrant K, Johnell O, Seeman E (2001) Age, gender and fragility fractures are associated with differences in quantitative ultrasound that are independent of bone mineral density. Bone 28:118–132
20. Duke PM, Litt IF, Gross RT (1980) Adolescents' self-assessment of sexual maturation. Pediatrics 66:918–920
21. Hanson BS, Larsson S (1991) Early experiences from the Kirseberg Public Health Project in Malmö, Sweden. An alcohol prevention campaign. Health Promot Int 6:111–119
22. Düppe H, Gärdsell P, Johnell O, Nilsson BE, Ringsberg K (1997) Bone mineral density, muscle strength and physical activity. A population-based study of 332 subjects aged 15–42 years. Acta Orthop Scand 68:97–103
23. Bergström E, Hernell O, Persson LÅ (1993) Dietary changes in Swedish adolescents. Acta Paediatr 82:472–480
24. Leger LA, Lambert J (1982) A maximal multistage 20-m shuttle run test to predict VO_2max. Eur J Appl Physiol 49:1–12
25. Leger LA, Mercier D, Gadoury C, Lambert J (1988) The multistage 20 metre shuttle run test for aerobic fitness. J Sports Sci 6:93–101
26. Liu NY, Plowman SA, Looney MA (1992) The reliability and validity of the 20-meter shuttle test in American students 12 to 15 years old. Res Q Exerc Sport 63:360–365
27. Kannus P, Haapasalo H, Sankelo M, Sievanen H, Pasanen M, Heinonen A, Oja P, Vuori I (1995) Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. Ann Intern Med 123:27–31
28. Hillam RA, Mosley J, Skerry TM (1994) Regional differences in bone strain. J Bone Miner Res 25:32
29. Hillam RA, Jackson M, Goodship AE, Skerry TM (1995) Regional differences in human bone strain in vivo. J Bone Miner Res 10:443
30. 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
31. Pettersson U (1999) Bone mass in the young athlete. Thesis. Umeå University Medical Dissertations, Umeå, Sweden
32. Bradney M, Karlsson MK, Duan Y, Stuckey S, Bass S, Seeman E (2000) Heterogeneity in the growth of the axial and appendicular skeleton in boys: implications for the pathogenesis of bone fragility in men. J Bone Miner Res 15:1871–1878
33. 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
34. Ruff CB, Walker A, Trinkaus E (1994) Postcranial robusticity in Homo. III: Ontogeny. Am J Phys Anthropol 93:35–54
35. Wittich A, Mautalen CA, Oliveri MB, Bagur A, Somoza F, Rotemberg E (1998) Professional football (soccer) players have a markedly greater skeletal mineral content, density and size than age- and BMI-matched controls. Calcif Tissue Int 63:112–117
36. Haapasalo H, Kontulainen S, Sievanen H, Kannus P, Jarvinen M, Vuori I (2000) Exercise-induced bone gain is due to enlargement in bone size without a change in volumetric bone density: a peripheral quantitative computed tomography study of the upper arms of male tennis players. Bone 27:351–357
37. Gonnelli S, Cepollaro C, Agnusdei D, Palmieri R, Rossi S, Gennari C (1995) Diagnostic value of ultrasound analysis and bone densitometry as predictors of vertebral de-for-mity in postmenopausal women. Osteoporos Int 5:413–418
38. Daly RM, Rich PA, Klein R, Bass S (1999) Effects of high-impact exercise on ultrasonic and biochemical indices of skeletal status: a prospective study in young male gymnasts. J Bone Miner Res 14:1222–1230