Osteoporos Int (1997) 7:525–532

Osteoporosis International

Original Article

Asynchrony Between the Rates of Standing Height Gain and Bone Mass Accumulation During Puberty

P.-E. Fournier[1], R. Rizzoli[1], D.-O. Slosman[2], G. Theintz[3] and J.-P. Bonjour[1]

[1]Division of Bone Diseases (formerly Clinical Pathophysiology), WHO Collaborating Center for Osteoporosis and Bone Diseases, Department of Internal Medicine; [2]Division of Nuclear Medicine, Department of Radiology; and [3]Division of Biology of Growth and Reproduction, Department of Pediatrics and Genetics, University Hospital, Geneva, Switzerland

Abstract. During puberty, the marked increases in both standing height and bone mass appear to be dissociated in time, the former occurring earlier than the latter. However, the age or pubertal stage at which this dissociation is maximal in girls as opposed to boys, and whether this dissociation is similar at all parts of the skeleton, are not clearly established. Standing height and bone mineral mass, as assessed by measuring areal bone mineral density (BMD), at the levels of the lumbar spine, femoral neck and midfemoral shaft, were measured in 98 females and 100 males between the ages of 9 and 19 years twice at a 1-year interval. In males, the greatest difference between height and BMD gains occurred in the 13–14 year age group and was more pronounced for the lumbar spine and femoral neck than for the midfemoral shaft. In females, the greatest difference was detectable at a younger age (11–12 year age group) and appeared to be of a lower magnitude than in males. In both genders, the maximal difference occurred during the period of peak height velocity, which corresponded to the pubertal stages P2–P3. Such a dissociation between the rates of statural growth and mineral mass accrual could define a state of relatively low bone mass and contribute to the higher incidence of fracture known to occur at the age and/or pubertal stage when this dissociation is maximal.

Keywords: Adolescence; Bone mineral density; Dual-energy X-ray absorptiometry; Peak height velocity

Correspondence and offprint requests to: Professor Jean-Philippe Bonjour, MD, Division of Bone Diseases (formerly Clinical Pathophysiology), Department of Internal Medicine, University Hospital, CH-1211 Geneva 14, Switzerland. Tel: +41 (22) 382 99 60. Fax: +41 (22) 382 99 73.

Introduction

The development of non-invasive techniques such as dual-energy X-ray absorptiometry (DXA) has made it possible to determine with precision and very low radiation exposure the pattern of bone mass, or more precisely of bone mineral mass accumulation at various sites of the axial and appendicular skeleton during infancy, childhood and adolescence [1–7]. During pubertal maturation, the pattern of bone mass accumulation differs markedly according to the skeletal site at which it is measured [2,4]. Indeed, in both female and male subjects aged 9–19 years, bone mass, as assessed by measuring areal bone mineral density (BMD) or bone mineral content (BMC), increases 4 to 6-fold in both the lumbar spine and proximal femur, but only 2-fold in the femoral shaft [4]. It is noteworthy that the increase in skeletal mass during puberty is mainly due to an increase in skeletal size rather than in the volumetric density of the bones (for review see [8]). Another important characteristic of bone mass accrual during puberty is its dissociation from the increase in standing height [2,4].

Various degrees of dissociation between these variables among individuals during puberty could explain the large height-independent variability seen in bone mass values in young healthy adults [9]. Furthermore, asynchrony between the rates of skeletal mass accrual and statural gain could be associated with a transient state of relatively low bone mass, and thereby with a decrease in the resistance to mechanical stress. Such a temporary delay in bone maturation with respect to longitudinal growth could be related to the sharp increase in the incidence of fractures observed during

puberty [10] with a maximal peak of incidence occurring at the ages of 12 and 14 years in girls and boys, respectively [11–13]. In the present study we analyzed the characteristics of this dissociation between bone mass gains and standing height changes, and studied the age during adolescence at which the shift was maximal in females and males depending on the skeletal site assessed.

Subjects and Methods

The cohort studied has been extensively described in two previous publications [2,4]. Briefly, the subjects (98 females and 100 males) aged 9–19 years were recruited through the State of Geneva Public Health Youth Service and among children whose parents were employees of the Geneva University Hospital. Each subject was examined twice at a 1-year interval in a prospective manner. The mean interval between the two anthropometric and bone mass measurements was 1.04 ± 0.01 and 1.03 ± 0.01 years in females and males, respectively. Both anthropometric and BMD values of the cohort are presented in Table 1. The following exclusion criteria were applied: no parental approval, chronic disease, malabsorption, congenital or acquired bone disease, chronic drug consumption, intensive practice of physical exercise (> 10 h/week), and weight/height ratio below the 3rd or above the 97th percentile. No subject had taken any prior therapy known to affect bone metabolism.

Height and weight were measured, and Tanner's stage assessed as previously described [2,4]. Bone mass was determined by measuring the areal BMD using DXA (Hologic QDR-1000 or QDR-1000W instruments). BMD was measured at three skeletal sites: the lumbar spine (L2–4, LS), femoral neck (FN) and midfemoral shaft (FS). The in vivo coefficients of variation of repeated measurements were 1.0%, 1.6% and 1.5% for LS, FN and FS BMD, respectively [14]. As already reported [15], at the level of FN the height (i.e the dimension parallel to the hip axis) of the region of interest (ROI) rectangular box was maintained constant from one examination to the other. Only the width (i.e. the dimension perpendicular to the hip axis) was adjusted to the growth of the bone in order to scan a similar proportion of soft tissue on each side of the femoral neck at both examinations [15]. The in vivo coefficients of variation of repeated measurements were 1.0%, 1.6% and 1.5% for LS, FN and FS BMD, respectively [14].

To further analyze the changes occurring at the level of LS, the height (mm) of the ROI was determined by multiplying the number of lines from the lower edge of L4 to the upper edge of L2 by a conversion factor (1 line = 1.003 mm) [15]. An estimate of the mean vertebral width was derived by dividing the scanned area by the height of L2–4 [15]. To assess to what extent the changes in areal BMD in LS would be due to gains in bone size as compared with volumetric bone mineral density, an estimate of this latter variable (bone mineral apparent density, BMAD) was calculated by dividing BMC by a volume derived from the projected area and height of L2–4 (volume = 3.1415 × area × area/4 × height) as previously described [16,17].

The relationship between bone mass accrual and standing height gain was established by using the data collected first cross-sectionally and then longitudinally. For the cross-sectional analysis, the 100% reference for the gains in BMD and standing height achieved during pubertal maturation was calculated as the difference between the mean values determined in the 18–20 year and 9–10 year groups at the first visit. As calculated from the results of Table 1, the 100% gains in the oldest (18–20 years) and youngest (9–10 years) age groups were as follows in females and males, respectively: Δ BMD LS, 0.418 and 0.363 g/cm^2; Δ BMD FN, 0.241 and 0.259 g/cm^2; Δ BMD FS, 0.550 and 0.682 g/cm^2; Δ Height, 29.0 and 37.7 cm. Then, the percentage gain in bone mass relative to the gain in height, achieved at the peak height velocity (PHV), was calculated. During puberty, PHV is known to occur at mean ages of approximately 12.5 and 14.5 years in females and males, respectively [12,18]. Thus, the data from the group of 12–13 year females and that of 14–15 year males (Table 1) were compared.

For the longitudinal analysis, the 100% reference represented the sum of the changes determined in each age group. As calculated from the results of Table 1, the 100% gains were as follows in females and males, respectively: sum Δ BMD LS, 0.330 and 0.403 g/cm^2; sum Δ BMD FN, 0.160 and 0.178 g/cm^2; sum Δ BMD FS, 0.389 and 0.694 g/cm^2; sum Δ Height, 24.2 and 37.2 cm. The same analysis was applied to the morphometric, BMC and BMAD data of L2–4 (Table 3); the 100% gains were as follows in females and males respectively: sum Δ Area, 13.46 and 22.06 cm^2; sum Δ Height, 2.59 and 3.57 cm; sum Δ Width, 0.42 and 0.85 cm; sum Δ BMC, 23.26 and 35.79 g; sum Δ BMAD, 0.078 and 0.067 g/cm^3.

Results

Cross-Sectional Study

At PHV, 51% and 78% of the total height gain occurring between the ages of 9–11 and 18–20 in females and males, respectively, had already been achieved (Fig. 1). In contrast, in the same age groups LS BMD gains were only 25% and 51% of the total 9–20 year changes in females and males, respectively. Analysis of FN BMD gains yielded results similar to those of LS BMD. The gain in FS BMD (32%) was similar to that observed for LS or FN BMD in the female subjects. However, in males the increase in FS BMD (66%) reached a level intermediate to those attained for height and LS or FN BMD (Fig. 1).

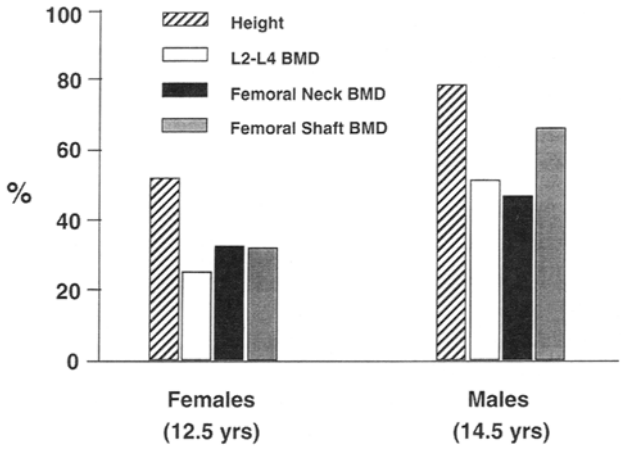

Fig. 1. Cumulative percentage gain in standing height and areal bone mineral density (BMD) achieved at the time of peak height velocity, which was attained in the 12–13 year female and 14–15 year male groups. One hundred percent corresponds to the difference between the 18–20 year and 9–11 year groups, as specified in Subjects and Methods.

Longitudinal Study

In Figs 2–4, the cumulative gains in LS, FN and FS BMD are compared with the increase in standing height relative to age. The relationship differed according to gender. Overall, there was a shift in height gains relative to gains in BMD, with bone mass accrual lagging behind changes in statural growth. In females this time lag between the gains in BMD and height was more pronounced for LS BMD (Fig. 2) than for FN BMD (Fig. 3), and very small for FS BMD (Fig. 4). In males the time lag in BMD was clearly detectable at the three skeletal sites, although it was somewhat less pronounced at FS than at either LS or FN (Figs 2–4).

The differences between the cumulative BMD changes and height gains at the three skeletal sites were then analyzed as a function of age (Fig. 5). In males, the greatest difference, i.e. the maximal delay in bone mass gain compared with standing height growth,

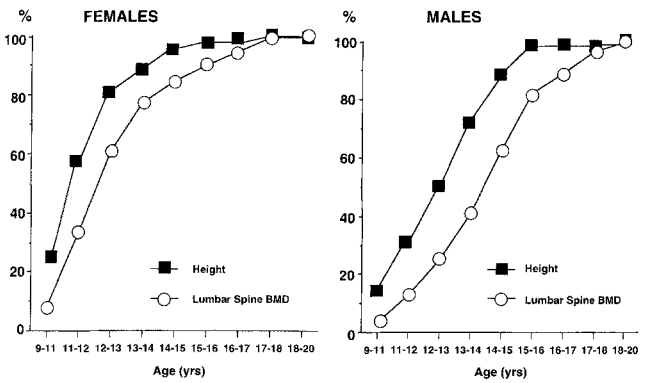

Fig. 2. Cumulative gain in lumbar spine BMD relative to standing height changes during adolescence. The values are expressed as the percentage difference between the 18–20 year and 9–11 year groups.

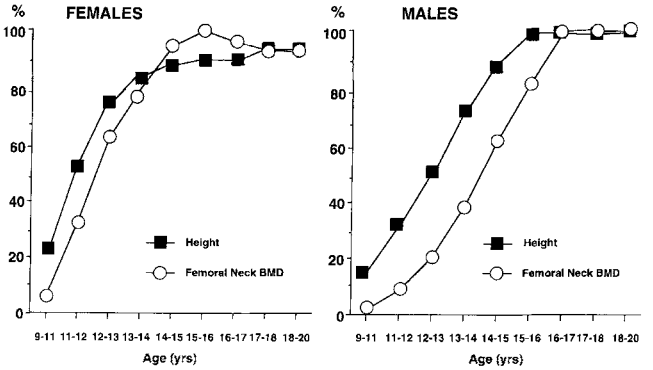

Fig. 3. Cumulative gain in femoral neck BMD relative to standing height changes during adolescence. The values are expressed as the percentage difference between the 18–20 year and 9–10 year groups.

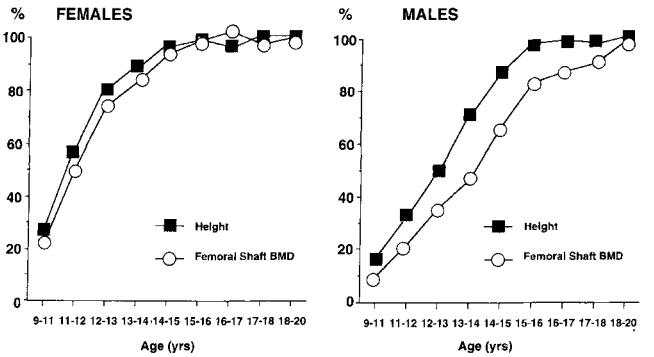

Fig. 4. Cumulative gain in midfemoral shaft BMD relative to standing height changes during adolescence. The values are expressed as the percentage difference between the 18–20 year and 9–10 year groups.

was observed in the 13–14 year age group. It amounted to 28%, 31% and 23% for LS, FN and FS BMD, respectively. In this male cohort, PHV was determined in the same 13–14 year age group: 7.9 ± 0.7 cm/year compared with 6.9 ± 0.7 cm/year and 5.9 ± 1.1 cm/year in the preceding (12–13 year) and following (14–15 year) age groups (Table 1). In females, the greatest difference in bone mass accumulation at both LS and FN levels compared with statural growth, was observed 2 years earlier than in males, i.e. in the 11–12 year group (Fig. 5). It was somewhat less pronounced than in males, with differences amounting to 22% and 20% for LS and FN BMD, respectively. In this female cohort, PHV was determined in the same 11–12 year age group: 7.5 ± 0.4 cm/year compared with 5.9 ± 0.4 cm/year and 6.1 ± 0.6 cm/year in the preceding (9–11 year) and following (12–13 year) age groups (Table 1). In females, the time lag betwen FS BMD gains and statural growth changes was much shorter than for the two other skeletal sites, the difference being not greater than 5–6% between the ages of 11 and 14 years, with no evident maximal value.

As previously reported [4], the maximal height increase was recorded at pubertal stage P2–P3 in both females and males, while the maximal bone mass gain was detected at stage P3–P4 (Table 2). Analyzed in terms of the percentage of total cumulative gain

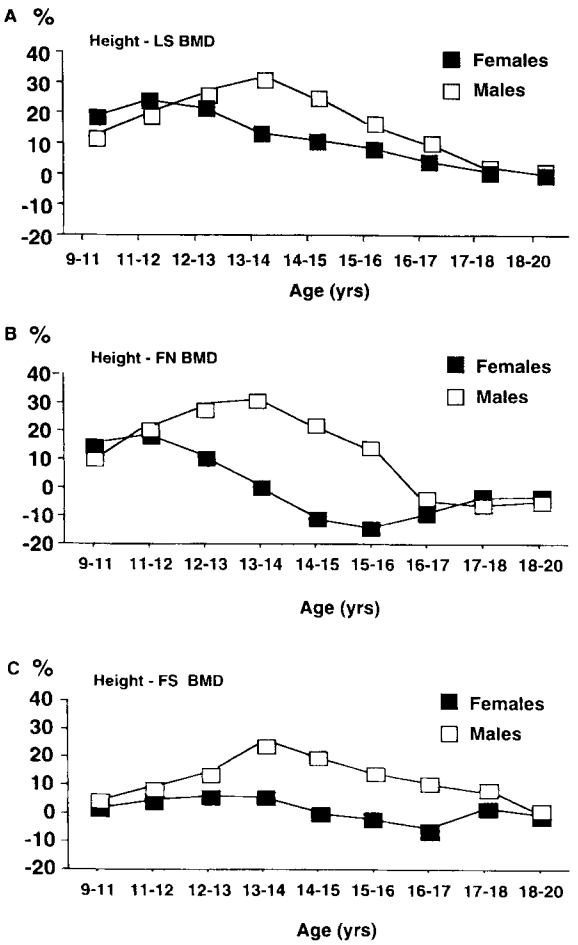

Fig. 5. Difference between the percentage standing height and BMD gains at the levels of the lumbar spine (**A**), femoral neck (**B**) and midfemoral shaft (**C**) BMD achieved at each time period. These values are derived from those presented in Figs 2, 3 and 4.

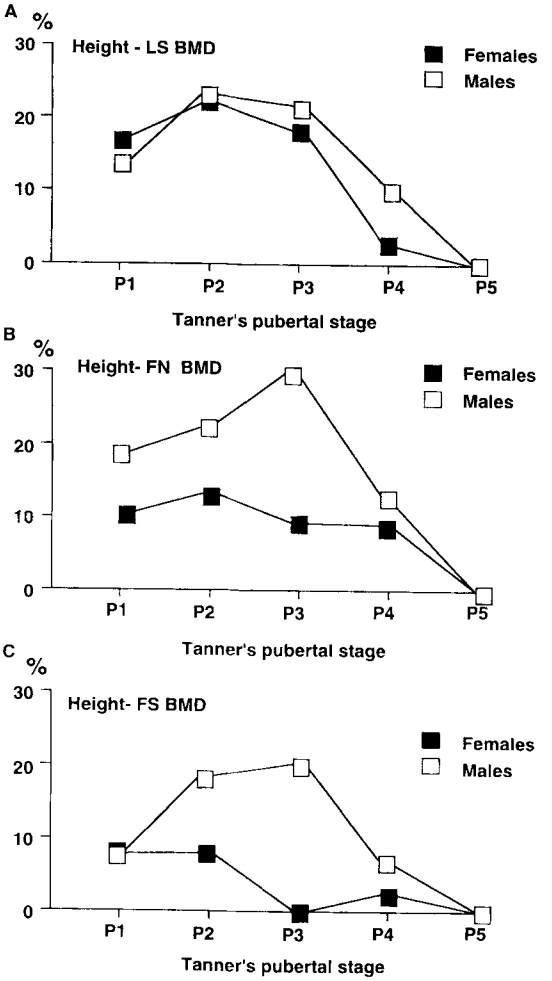

Fig. 6. Difference between the percentage standing height and BMD gains at the levels of the lumbar spine (**A**), femoral neck (**B**) and midfemoral shaft (**C**) BMD achieved at each pubertal stage.

Table 1. Standing height and areal bone mineral density according to chronological age

Age (years)	*n*	BMD LS (g/cm^2)	Δ BMD LS (g/cm^2/year)	BMD FN (g/cm^2)	Δ BMD FN (g/cm^2/year)	BMD FS (g/cm^2)	Δ BMD FS (g/cm^2/year)	Height (cm)	Δ height (cm/year)
Females									
9–11	20	0.674±0.015	0.025±0.006	0.698±0.017	0.011±0.007	1.274±0.024	0.085±0.012	138.39±1.66	5.85±0.35
11–12	10	0.731±0.021	0.085±0.015	0.728±0.018	0.045±0.012	1.373±0.048	0.111±0.024	147.47±2.15	7.54±0.36
12–13	10	0.780±0.036	0.091±0.007	0.776±0.035	0.052±0.013	1.451±0.049	0.093±0.015	153.41±2.70	6.05±0.62
13–14	9	0.904±0.025	0.055±0.012	0.810±0.025	0.030±0.009	1.695±0.043	0.037±0.018	160.87±1.68	2.20±0.32
14–15	11	1.020±0.042	0.024±0.011	0.905±0.038	0.025±0.012	1.724±0.054	0.040±0.009	165.64±1.81	1.26±0.36
15–16	14	1.025±0.037	0.018±0.011	0.934±0.029	0.010±0.009	1.770±0.023	0.019±0.010	164.29±1.36	0.70±0.25
16–17	10	0.995±0.027	0.015±0.008	0.917±0.021	−0.007±0.010	1.778±0.032	0.014±0.014	166.65±2.55	0.12±0.23
17–18	7	1.013±0.029	0.016±0.007	0.892±0.031	−0.005±0.014	1.806±0.044	−0.018±0.016	165.24±2.53	0.47±0.28
18–20	7	1.092±0.039	0.001±0.014	0.938±0.015	−0.001±0.008	1.824±0.033	0.009±0.009	167.37±1.92	0.03±0.27
Males									
9–11	22	0.671±0.013	0.014±0.003	0.754±0.015	0.003±0.007	1.304±0.025	0.067±0.010	141.09±1.30	5.20±0.21
11–12	8	0.698±0.021	0.037±0.007	0.812±0.017	0.012±0.013	1.408±0.031	0.083±0.014	146.64±3.04	5.81±0.33
12–13	12	0.736±0.025	0.049±0.013	0.786±0.020	0.021±0.010	1.443±0.042	0.096±0.019	154.66±2.57	6.93±0.69
13–14	10	0.743±0.021	0.065±0.012	0.812±0.021	0.032±0.016	1.575±0.045	0.075±0.017	153.91±2.18	7.87±0.68
14–15	10	0.857±0.028	0.087±0.017	0.875±0.032	0.041±0.019	1.753±0.043	0.139±0.025	170.56±1.32	5.93±1.05
15–16	14	0.929±0.045	0.080±0.008	0.939±0.055	0.036±0.016	1.757±0.049	0.116±0.012	173.78±2.18	4.39±0.75
16–17	9	1.029±0.038	0.028±0.010	1.000±0.027	0.033±0.019	2.014±0.047	0.032±0.010	175.30±3.39	0.43±0.30
17–18	7	1.004±0.048	0.029±0.009	1.042±0.057	0.002±0.010	1.979±0.056	0.020±0.023	175.96±1.13	−0.06±0.31
18–20	8	1.035±0.036	0.014±0.013	1.013±0.051	−0.001±0.009	1.985±0.062	0.065±0.027	178.75±2.56	0.71±0.39

Areal bone mineral density (BMD) was determined at the level of the lumbar spine (L2–4, LS), femoral neck (FN) and midfemoral shaft (FS). Values are means ± SEM. Δ refers to the change achieved during the next year. Height = standing height.

Table 2. Standing height and areal bone mineral density gain during pubertal maturation

P	*n*	Δ BMD LS (g/cm^2/year)	Δ BMD FN (g/cm^2/year)	Δ BMD FS (g/cm^2/year)	Δ height (cm/year)
Females					
P1	18	0.018 ± 0.004	0.014 ± 0.007	0.061 ± 0.010	5.66 ± 0.29
P2	12	0.079 ± 0.011	0.033 ± 0.013	0.124 ± 0.014	7.75 ± 0.44
P3	3	0.098 ± 0.011	0.042 ± 0.005	0.137 ± 0.017	7.03 ± 0.55
P4	7	0.098 ± 0.014	0.019 ± 0.013	0.056 ± 0.027	4.17 ± 0.66
P5	58	0.022 ± 0.005	0.015 ± 0.005	0.025 ± 0.006	0.97 ± 0.20
Males					
P1	29	0.016 ± 0.003	0.001 ± 0.006	0.062 ± 0.008	5.12 ± 0.17
P2	18	0.051 ± 0.009	0.027 ± 0.010	0.084 ± 0.012	7.17 ± 0.42
P3	10	0.091 ± 0.009	0.031 ± 0.008	0.137 ± 0.017	8.45 ± 0.60
P4	16	0.078 ± 0.012	0.039 ± 0.017	0.141 ± 0.018	4.46 ± 0.66
P5	27	0.032 ± 0.007	0.018 ± 0.008	0.040 ± 0.008	0.71 ± 0.37

Areal bone mineral density (BMD) was determined at the level of the lumbar spine (L2–4, LS), femoral neck (FN) and midfemoral shaft (FS). Values are means ± SEM. Δ refers to the change achieved during the next year. P = pubertal stage.

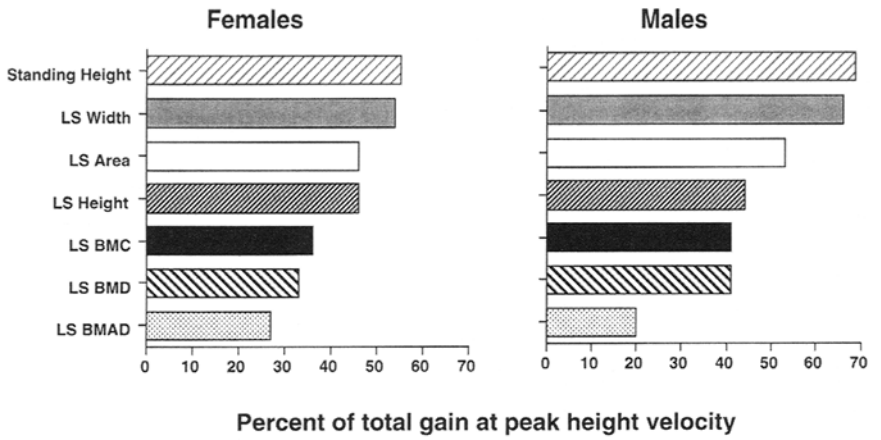

Fig. 7. Relative gains in morphometric, bone mass and bone density of L2–4 (LS) as compared with standing height at peak height velocity. The *bars* correspond to the percentage at peak height velocity of the total gain achieved between age 9–11 and 18–20 years for L2–4 height, mean width, scanned area, bone mineral content (BMC), areal bone mineral density (BMD) and the estimate of volumetric bone mineral density (BMAD). The percentages were calculated from data presented in Table 3. The 100% gains of the lumbar variables are indicated in Subjects and Methods.

Table 3. Lumbar spine variables

Age (years)	*n*	Area (cm^2)	Δ Area (cm^2/year)	Height (cm)	Δ Height (cm/year)	Width (cm)	Δ Width (cm/year)	BMC (g)	Δ BMC (g/year)	BMAD (g/cm^3)	Δ BMAD (g/cm^3/year)
Females											
9–11	20	27.16 ± 0.78	2.28 ± 0.23	8.05 ± 0.11	0.40 ± 0.05	3.37 ± 0.06	0.11 ± 0.02	18.41 ± 0.82	2.34 ± 0.36	0.255 ± 0.005	0.002 ± 0.002
11–12	10	31.60 ± 1.39	3.96 ± 0.32	8.65 ± 0.21	0.80 ± 0.19	3.64 ± 0.10	0.12 ± 0.06	23.09 ± 1.20	5.94 ± 0.74	0.258 ± 0.011	0.019 ± 0.005
12–13	10	32.47 ± 1.56	3.43 ± 0.21	9.03 ± 0.21	0.58 ± 0.04	3.58 ± 0.10	0.14 ± 0.02	25.70 ± 2.22	5.94 ± 0.45	0.277 ± 0.009	0.020 ± 0.002
13–14	9	38.53 ± 1.58	1.70 ± 0.48	10.03 ± 0.31	0.30 ± 0.10	3.86 ± 0.16	0.05 ± 0.03	34.93 ± 1.92	3.90 ± 0.93	0.301 ± 0.012	0.013 ± 0.004
14–15	11	42.47 ± 1.41	1.20 ± 0.42	10.31 ± 0.17	0.18 ± 0.06	4.11 ± 0.08	0.05 ± 0.03	43.67 ± 2.93	2.11 ± 0.80	0.316 ± 0.010	0.004 ± 0.003
15–16	14	42.50 ± 0.86	0.60 ± 0.29	10.43 ± 0.13	0.14 ± 0.05	4.07 ± 0.06	0.00 ± 0.02	43.83 ± 2.28	1.33 ± 0.62	0.320 ± 0.009	0.006 ± 0.003
16–17	10	43.58 ± 1.14	0.27 ± 0.36	10.53 ± 0.18	0.09 ± 0.03	4.14 ± 0.07	−0.01 ± 0.03	43.28 ± 1.49	0.90 ± 0.53	0.307 ± 0.011	0.005 ± 0.004
17–18	7	41.91 ± 1.06	0.28 ± 0.29	10.39 ± 0.16	0.06 ± 0.06	4.03 ± 0.06	0.01 ± 0.02	42.47 ± 1.60	0.96 ± 0.31	0.320 ± 0.010	0.005 ± 0.003
18–20	7	45.84 ± 1.85	−0.25 ± 0.20	10.56 ± 0.25	0.05 ± 0.01	4.34 ± 0.11	−0.04 ± 0.02	50.01 ± 2.47	−0.16 ± 0.62	0.321 ± 0.013	0.003 ± 0.005
Males											
9–11	22	28.37 ± 0.60	1.73 ± 0.22	8.22 ± 0.12	0.38 ± 0.05	3.46 ± 0.06	0.05 ± 0.02	19.13 ± 0.68	1.64 ± 0.22	0.249 ± 0.006	0.002 ± 0.001
11–12	8	31.68 ± 1.36	2.42 ± 0.36	8.51 ± 0.21	0.34 ± 0.05	3.71 ± 0.09	0.13 ± 0.03	22.28 ± 1.51	2.99 ± 0.41	0.240 ± 0.005	0.004 ± 0.002
12–13	12	32.81 ± 1.44	3.08 ± 0.57	8.83 ± 0.17	0.46 ± 0.09	3.70 ± 0.10	0.14 ± 0.04	24.36 ± 1.85	4.23 ± 0.97	0.254 ± 0.007	0.006 ± 0.004
13–14	10	33.06 ± 1.09	4.38 ± 0.52	9.02 ± 0.26	0.55 ± 0.08	3.67 ± 0.09	0.24 ± 0.05	24.61 ± 1.18	5.77 ± 0.85	0.258 ± 0.007	0.001 ± 0.004
14–15	10	43.66 ± 1.45	3.86 ± 0.84	10.57 ± 0.32	0.39 ± 0.12	4.15 ± 0.13	0.21 ± 0.04	37.71 ± 2.58	7.32 ± 1.49	0.265 ± 0.011	0.012 ± 0.004
15–16	14	43.64 ± 1.85	4.25 ± 0.48	10.30 ± 0.22	1.16 ± 0.38	4.22 ± 0.10	−0.01 ± 0.13	41.29 ± 3.48	7.62 ± 0.61	0.280 ± 0.011	0.028 ± 0.011
16–17	9	49.46 ± 2.60	0.93 ± 0.23	10.76 ± 0.29	0.13 ± 0.03	4.58 ± 0.13	0.03 ± 0.03	51.30 ± 4.25	2.43 ± 0.63	0.287 ± 0.011	0.006 ± 0.002
17–18	7	50.07 ± 0.94	0.67 ± 0.46	10.87 ± 0.12	0.00 ± 0.03	4.07 ± 0.10	0.06 ± 0.04	50.33 ± 0.27	2.26 ± 0.70	0.278 ± 0.015	0.004 ± 0.004
18–20	8	51.11 ± 1.59	0.75 ± 0.26	11.18 ± 0.15	0.16 ± 0.04	4.57 ± 0.10	0.00 ± 0.03	53.00 ± 2.77	1.53 ± 0.92	0.289 ± 0.010	0.003 ± 0.002

Values are means ± SEM. They correspond to the scanned area, height and mean width of L2–4.
Bone mineral apparent density (BMAD) was derived from the formula: BMC/volume, where BMC is bone mineral content. Volume = (3.1415 × area × area)/(4 × height).

achieved in stages P1–P5, the maximal differences between bone mass and height gains were recorded at stage P2–P3 (Fig. 6). The difference between LS BMD and height gains recorded in P3–P3 females was fully comparable to that derived from the measurements made in males at the same stage of pubertal maturation. For the two other sites (FN and FS) the sex-related difference depicted in Fig. 5B and C from ages 13 to 16 years was still apparent when the data were analyzed in relation to pubertal stage (Fig. 6B, C). The delay in bone mass accumulation relative to height gain remained less pronounced in P2–P3 females than in males at the same stage of pubertal maturation.

At the lumbar spine level analysis of the longitudinal morphometric, BMC and BMAD data presented in Table 3 in terms of relative gains at PHV is illustrated in Fig. 7. It appears that at PHV in both genders the lag behind the standing height gain is more pronounced for LS BMAD, BMC and BMD than for the dimensions of the vertebrae.

Discussion

Asynchrony Between Bone Mass and Height Gain

The foregoing analysis confirms the existence during pubertal maturation of a time lag between bone mineral mass acquisition, as assessed by DXA at different skeletal sites containing various proportions of trabecular and cortical bony tissue, and statural growth. This analysis has made it possible to quantify the difference in statural and bone mass maturation and to determine at what age and pubertal stage it reaches its maximum. The main results of this analysis indicate that overall the delay is of a greater duration in males than females and is also more pronounced in the former, particularly at the levels of the femoral neck and midfemoral shaft. The delay is maximal at PHV, i.e. at the ages of 11–12 years in females and 13–14 years in males. These ages correspond in both genders to pubertal stages P2–P3. The period during which bone mass accrual lags behind the gain in standing height could modify the resistance to mechanical stress at certain sites of the skeleton. Indeed, one can consider this period as a phase during which the bones are relatively 'thin' in comparison with the mass of soft body tissue. Analysis of the morphometric and bone mineral density variables at the lumbar spine level suggests that an important asynchrony occurs at PHV between the accumulation rate of mineralized tissue and the growth in size of the vertebrae. Therefore, it is interesting to discuss the results of our analysis in relation to the risk of fracture during adolescence.

Incidence of Fracture During Adolescence

Each year, 1 out of 7 children undergoes a medical examination because of trauma. Among those having such a medical examination, 6 out of 10 are males. This sex ratio appears to remain constant from age 2 to 15 years, as reported by Westfelt who recorded 12265 accidents in the area of Göteborg in Sweden [19]. In injured children, fractures represent between 20% and 30% of all the diagnoses. Other epidemiological reports indicate that for all recorded fractures during childhood and adolescence the ratio of males to females is 2.7. However, in the adolescent group the male/female ratio increases to 5.5 [20]. In another epidemiological study also conducted in a Sweden urban population, the overall incidence of fractures was found to be 165 in females and 257 in males per 10000 children and adolescents aged less than 17 years [21]. The incidence of fractures in male subjects increased steeply between the ages of 9 and 14 [21]. This increase was mainly due to a higher incidence of wrist, hand, ankle and foot fractures resulting to a large extent from low-energy trauma. In this report, the possibility was suggested that the increased fracture incidence recorded between the ages of 9 and 14 in males was related to some changes in mechanical resistance, particularly for wrist fractures [21]. In another more recent Canadian epidemiological study concerning fractures of the distal part of the radius during childhood and adolescence, the age of peak of fracture incidence corresponded to the age of PHV, in both females and in males [12]. This association could be attributed to a transient period of relative bone weakness due to a putative dissociation between rates of skeletal growth and bone mineralization [12]. In a still more recent Belgian investigation in boys, a similar association between peak of fracture incidence and PHV was documented [13]. Interestingly, the increased fracture rate did not appear to be due to a higher level of physical activity during this period of adolescence.

Bone Mass and Fracture During Adolescence

In the abovementioned Belgian study [13], cortical thickness was measured at the level of the second metacarpal bone. No significant difference between the fractured and non-fractured groups was found. But, as mentioned by the authors, radiographic measurements of cortical thickness provide only indirect and imprecise estimates of bone mineral content or density and are poorly correlated with absorptiometry measurements [13]. Furthermore, an increase in the porosity of the cortical shell could contribute to the transient fragility observed during the spurt of adolescent growth, as postulated by Parfitt [22].

In a very small cohort, bone mass was evaluated by determining the areal BMD at the level of the proximal radius using single photon absorptiometry (SPA) in children with fractures compared with matched non-fractured controls [23]. SPA was performed about 16 months after the fracture. A reduced bone mass relative to matched controls was found in 12 out of 17 children with a limb fracture [23]. In another study, a statistically non-significant reduction in bone mass at the level of the femoral neck and Ward's triangle was reported [24]. Finally, in a cohort of 90 children with fracture, bone

mass was found to be reduced by 8% relative to matched controls in the subgroup of fractures produced by low-energy trauma [21].

Bone mass is an important but not the only determinant of bone strength. During puberty several major transformations occur, including marked increases in standing height, muscle mass and strength. The total body moment of inertia is modified in a curvilinear manner, with a marked acceleration during the 10–15 year period [25]. These modifications per se, and the relatively poor judgement and recklessness frequently seen in adolescents, may lead to them having a greater tendency to fall, with a corresponding increase in the risk of incurring fracture.

Other Expressions of Bone Fragility

A number of skeletal pathological situations are characteristic of the period of PHV. In Scheuermann's disease, transient bone fragility could explain the disruption of the endochondral plate. Bone mass was determined in patients suffering from this disease without showing definite results [26]. As compared with age-matched controls, a significantly lower bone mass at the level of the lumbar spine was recorded in 10 patients suffering from Scheuermann's disease [26]. In another report, trabecular bone density as measured by quantitative computerized tomography (QCT) was not found to be diminished [27]. Scoliosis and stress fractures were also mentioned as possible consequences of inadequate calcification during the rapid phase of adolescent growth [28].

It is not known whether adolescents experiencing low-energy fractures display a particularly important dissociation between bone mass accrual and statural height gain, relative to age- and pubertal stage-matched non-fractured subjects. Bone mass has only been determined in a few studies [13,21,23,24]. Definite conclusions are difficult to draw since in these studies the cohorts were rather small, the age ranges were wide, fractures at all body sites were pooled, bone mass was not always determined with precise and accurate techniques, and measurements were sometimes performed long after the fracture occurred. Prospective studies aimed at determining the magnitude of the asynchrony between bone mass accrual and height gain in children and adolescents experiencing low-energy fractures should be considered in order to document this 'transient bone fragility hypothesis'. Such studies will require longitudinal prospective investigations involving a large number of subjects recruited at the beginning of pubertal maturation.

Acknowledgements. We are indebted to Dr P. Hazeghi, MD, and to the Geneva Public Youth Service for the recruitment of the subjects, to the team of the bone densitometry unit and to Mrs S. Gardiol, M.-C. Brandt and M. Perez for their help in preparing the manuscript. This work was supported by the Swiss National Science Foundation (grants nos. 32–32415.91 and 31–40758.94).

References

1. Glastre C, Braillon P, David L. Cochat P, Meunier PJ, Delmas PD. Measurement of bone mineral content of the lumbar spine by dual-energy X-ray absorptiometry in normal children: correlations with growth parameters. J Clin Endocrinol Metab 1990;70:1330–3.
2. Bonjour JP, Theintz G, Buchs B, Slosman D, Rizzoli R. Critical years and stages of puberty for spinal and femoral bone mass accumulation during adolescence. J Clin Endocrinol Metab 1991;73:555–63.
3. Katzman DK, Bachrach LK, Carter DR, Marcus R. Clinical and anthropometric correlates of bone mineral acquisition in healthy adolescent girls. J Clin Endocrinol Metab 1991;73:1332–9.
4. Theintz G, Buchs B, Rizzoli R, Slosman D, Clavien H, Sizonenko PC, Bonjour JP. Longitudinal monitoring of bone mass accumulation in healthy adolescents: evidence for a marked reduction after 16 years of age at the levels of lumbar spine and femoral neck in females subjects. J Clin Endocrinol Metab 1992;75:1060–5.
5. Salle BL, Braillon P, Glorieux FH, Brunet J, Cavero E, Meunier PJ. Lumbar bone mineral content measured by dual-energy X-ray absorptiometry in newborns and infants. Acta Paediatr 1992;81:953–8.
6. Grimston SK, Morrison K, Harder JA, Hanley DA. Bone mineral density during puberty in Western Canadian children. Bone Miner 1992;19:85–96.
7. Rubin K, Schirduan V, Gendreau P, Sarfarazi M, Mendola R, Dalsky G. Predictors of axial and peripheral bone mineral density in healthy children and adolescents, with special attention to the role of puberty. J Pediatr 1993;123:863–70.
8. Bonjour JP, Theintz G, Law F, Slosman D, Rizzoli R. Peak bone mass. Osteoporos Int 1994;4(Suppl 1):S7–13.
9. Fournier PE, Rizzoli R, Slosman DO, Buchs B, Bonjour JP. Relative contribution of vertebral body and posterior arch in female and male lumbar spine peak bone mass. Osteoporos Int 1994;4:264–72.
10. Alffram PA, Bauer GCH. Epidemiology of fractures of the forearm: a biomechanical investigation of bone strength. J Bone Joint Surg Am 1962;44:105–14.
11. Landin L, Nilsson BE. Bone mineral content in children with fractures. Clin Orthop Rel Res 1983;178:292–6.
12. Bailey DA, Wedge JH, McCulloch RG, Martin AD, Bernhardson SC. Epidemiology of fractures of the distal end of the radius in children as associated with growth. J Bone Joint Surg Am 1989;71:1225–31.
13. Blimkie CJR, Lefevre J, Beunen GP, Renson R, Dequeker J, Van Damme P. Fractures, physical activity, and growth velocity in adolescent Belgian boys. Med Sci Sports Exerc 1993;25:801–8.
14. Slosman DO, Rizzoli R, Donath A, Bonjour JP. Vertebral bone mineral density measured laterally by dual-energy X-ray absorptiometry. Osteoporos Int 1990;1:23–9.
15. Bonjour J-P, Carrie A-L, Ferrari S, Clavien H, Slosman D, Theintz G. Rizzoli R. Calcium-enriched foods and bone mass growth in prepubertal girls: a randomized, double-blind, placebo-controlled trial. J Clin Invest 1997;99:1287–94.
16. Katzman DK, Bachrach LK, Carter DR, Marcus R. Clinical and anthropometric correlates of bone mineral acquisition in healthy adolescent girls. J Clin Endocrinol Metab 1991;73:1332–9.
17. Carter DR, Bouxsein ML, Marcus R. New approaches for interpreting projected bone densitometric data. J Bone Miner Res 1992;7:137–45.
18. Prader A, Largo RH, Molinari L, Issler C. Physical growth of Swiss children from birth to 20 years of age. Helv Paediatr Acta 1988;43(Suppl 52):1–125.
19. Nathorst Westfelt JAR. Environmental factors in childhood accidents: a prospective study in Goeteborg, Sweden. Acta Paediatr Scand 1982;7(Suppl 291):1–75.
20. Cheng JCY, Shen WY. Limb fracture pattern in different pediatric age groups: a study of 3350 children. J Orthop Trauma 1993;7:15–22.
21. Landin LA. Fracture patterns in children: analysis of 8682

fractures with special reference to incidence, etiology and secular changes in a Swedish urban population 1950–1979. Acta Orthop Scand 1983;54(Suppl 202):1–109.
22. Parfitt AM. The two faces of growth: benefits and risks to bone integrity. Osteoporos Int 1994;4:382–98.
23. Chan GM, Hess M, Hollis J, Book LS. Bone mineral status in childhood accidental fractures. Am J Dis Child 1984;138:569–70.
24. Cook SD, Harding AF, Morgan EL, et al. Association of bone mineral density and pediatric fractures. J Pediatr Orthop 1987;7:424–7.
25. Jensen RK. The growth of children's moment of inertia. Med Sci Sports Exerc 1986;18:440–5.
26. Lopez RA, Burke SW, Levine DB, Schneider R. Osteoporosis in Scheuermann's disease. Spine 1988;13:1099–103.
27. Gilsanz V, Gibbens DT, Carlson M, King J. Vertebral bone density in Scheuermann's disease. J Bone Joint Surg Am 1989;71:894–7.
28. Warren MP, Brooks-Gunn J, Hamilton LH, Waren LF, Hamilton WG. Scoliosis and fractures in young ballet dancers. N Engl J Med 1986;314:1348–53.

Received for publication 19 September 1006
Accepted in revised form 22 May 1997