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A 3-Year Longitudinal Study of the Effect of Physical Activity on the Accrual of Bone Mineral Density in Healthy Adolescent Males

A. Gustavsson,[1,2] K. Thorsen,[2,3] P. Nordström[2,4]

[1]Medicine, Department of Public Health and Clinical Medicine, Umeå University, 901 87 Umeå, Sweden
[2]Sports Medicine, Department of Surgical and Perioperative Sciences, Umeå University, 901 87 Umeå, Sweden
[3]Department of Musculoskeletal Research, National Institute for Working Life, Umeå University, 901 87 Umeå, Sweden
[4]Department of Geriatric Medicine, Umeå University, 901 87 Umeå, Sweden

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Abstract. It has previously been suggested that physical activity predominantly influences the accumulation of bone density before puberty. The purpose of the present study was to examine the effect of physical activity on the accumulation of bone mass in male athletes between 16 and 19 years of age. The cohort studied consisted of 12 badminton players (aged 16.1 ± 0.5), 20 ice hockey players (aged 16.1 ± 0.5), and 24 age-matched controls (aged 16.1 ± 0.6). The bone mineral density (BMD, g/cm^2) of the total body, spine, dominant and nondominant humerus, head and femoral neck was measured twice with a 3-year interval by dual energy X-ray absorptiometry (DXA). In addition, at the femoral neck, volumetric bone mineral density (vBMD, mg/cm^3) was estimated. At baseline, the athletes as a whole group had significantly higher BMD at the total body (P = 0.03), dominant (P = 0.006) and nondominant humerus (P = 0.009) and femoral neck (P = 0.007) compared to the controls. At the 3-year followup, the athletes had significantly higher BMD at all sites (total body; P = 0.003, spine; P = 0.02, dominant humerus; P = 0.001, nondominant humerus; P = <0.001, femoral neck; P = 0.001) except for the head (P = 0.91) compared with controls. The athletes also had higher vBMD at the femoral neck compared with the controls (P = 0.01). Furthermore, to be an athlete was found to be independently associated with a higher increase in nondominant humerus BMD (β = 0.24; P < 0.05) and femoral neck BMD (β = 0.30; P < 0.05) compared with the controls, during the study period. In summary, these results suggests that it is possible to achieve continuous gains in bone mass in sites exposed to osteogenic stimulation after puberty in males by engaging in weight-bearing physical activity.

Key words: Bone mineral density — Peak bone mass — Boys, physical activity

Osteoporosis is an increasing global health care problem, characterized by a reduction in bone mass, microstructural deterioration with advancing age, and an increase in fracture rate [1]. Knowledge of factors affecting the incidence of osteoporosis is critical for the possibility to successfully minimize the impact of the fractures that are an important cause of mortality and painful impairment in the western world [2–4].

Genetic factors have been estimated to be responsible for about 70% of the variance in bone mass[5–8] but the remaining 30% is possibly influenced by optimizing factors such as nutritional intake and physical activity, thereby decreasing the risk of osteoporosis and its consequences [9].

Peak bone mass is achieved in the end of the second decade of life, with a progressive loss of bone thereafter and may be accountable for more than half the variation in bone mass to at least 65 years of age [10, 11]. Thus, peak bone mass may influence the risk of osteoporosis [12–13]. Physical activity during adolescence is well known to influence peak bone mass [14, 15] and has many possible positive implications on effecting the future risk of osteoporosis considering that it not only optimizes the peak BMD but it could also establish a be- havioral pattern that may continue into adulthood [16].

Experimental studies have shown that physical activity should be weight-bearing and dynamic, with high magnitude strains applied at a high rate with relatively few repetitions [17–20], and probably from different angles [21, 22], to optimize the osteogenic effect. It has also been demonstrated that this kind of physical activity clearly has a positive effect on bone accretion before and during puberty [14, 15], but there is very little information about the possible role of physical activity in promoting continued bone accretion at the postpubertal period. Furthermore, the main part of the studies

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Correspondence to: A. Gustavsson; E-mail: anna.gustavsson@idrott.umu.se

executed are performed with girls as subjects [23–25], and the results from these studies may not be completely applicable to boys' accretion of bone mass and the potential role of physical activity in promoting continued bone mass accrual after puberty.

The purpose of this longitudinal study was to investigate the effect of physical activity on bone accumulation mass in young males just passed puberty in a cohort of young athletes consisting of badminton and ice hockey players, and age-matched controls.

Subjects and Methods

Subjects

This study was performed in Umeå, in the northeastern part of Sweden. From advertisement and information in schools and local sports clubs, 82 healthy Caucasian boys were recruited for the present study, and 75 of them could be followed up after 3 years. Since the aim of this study was to investigate differences in bone accrual between athletes and controls, the athletes and controls were chosen to be similar in age and height at the entry of this study. The participants in the athlete group had to continue training throughout the study period, leaving fiftysix boys (aged 16.1 ± 0.5 years) (mean ± SD) to be included in this longitudinal study. Using a standardized questionnaire, smoking habits, known illnesses, and any medications were recorded together with type and amount of physical activity that was reported as an average amount of training hours per week. The questionnaire also contained questions about starting age of training for the athletes. In the athletes group, the head coaches were interviewed to validate the type and amount of training that was included in their training program.

In the athletes group the recruitment took place at local badminton and ice hockey clubs. At baseline, the average amount of training per week was 5.3 ± 1.4 h for the 12 badminton players (aged 16.1 ± 0.5) and 9.4 ± 2.0 h for the 20 hockey players (aged 16.1 ± 0.5), where the physical activity mainly consisted of training or matches and some additional weight and aerobic training at the beginning of the study. The control group consisted of 24 boys (aged 16.1 ± 0.6) recruited from two high schools. Their main forms of activity consisted of playing soccer and floor ball and distance running and weight training. The total amount of weight-bearing physical activity during their spare time was estimated at 1.6 ± 1.2 h/week. An inclusion criterion in the control group was that they did not participate in any organized physical training besides the mandatory educational physical activity within the school curriculum. In the control group, 2 subjects reported smoking.

All 56 boys also participated in 2 h of physical education in school each week. The participants' pubertal stage according to Tanner [26] was investigated at 17 years of age [27]. The groups were not significantly different ($P = 0.88$). All were judged to have passed the pubertal growth spurt period, based on development of pubertal hair growth and genitalia. The subjects axillary hair growth and growth of beard was also judged. Weight and height were measured using standardized equipment. None of the boys had any disease or were taking medication known to affect bone metabolism.

After a mean period of 3 years, the original participants were approached and asked if they could participate in a follow-up. The same study protocol was used for the follow-up as for the baseline measurements. All data were collected at visits at the Sports Medicine Unit at Umeå University. Informed consent was given by all the participants and the study protocol was approved by the Ethical Committee of the Medical Faculty, Umeå University.

Bone Mineral Density

Bone mineral density (BMD; g/cm^2) of the total body, spine, dominant and nondominant humerus, head and the femoral neck, and bone mineral content (BMC; g) and bone area (cm^2) of the right femoral neck were measured using the same Lunar DPX-L (Lunar Co, WI, USA) DXA, software version 1.3y. The volumetric bone mineral density (vBMD; mg/cm^3) of the femoral neck was estimated from bone mineral content (BMC) and the estimated volume. The vBMD is estimated as (BMC/volume) × 1000 (mg/cm^3). It was assumed that the femoral neck site was cylindrical in shape and the volume of this cylinder was then estimated from the area and height. The accuracy and precision of DXA have been discussed in detail by others [28, 29]. In our laboratory the CV-value (standard deviation/mean) is 0.7–2.0%, depending on application [30]. Furthermore, the equipment is calibrated each day using a standardized phantom to detect drifts in bone density measurements.

Statistical Analysis

Differences in age anthropometrical data, physical activity, and bone density among the three groups were investigated using an analysis of variance (ANOVA), with Bonferroni's post hoc test for multiple comparisons. Differences between the two groups were investigated using a Student's *t*-test for independent samples. The independent predictors of the change in bone density of the different sites during the 3-year study period were analyzed in the athletes and controls using linear regression. The SPSS package, version 9.0 for PC, was used for statistical analyses. A *P*-value less than 0.05 was considered significant.

Results

Anthropometrical measures, hours of physical activity and bone density for the controls, athletes, and subgroups of badminton and ice hockey players, are presented at 16 years of age in Table 1. Starting age of training for badminton or ice hockey was not related to BMD of any weight-bearing site or changes thereof in this study. There was no significant difference between the groups in age, weight, or height at the entry of the study. At baseline, the athletes as a whole group (n = 32) had a significantly higher BMD of the total body ($P = 0.03$), dominant ($P = 0.006$) and nondominant humerus ($P = 0.009$), and femoral neck ($P = 0.007$) compared with controls. The subgroup of badminton players had significantly higher BMD at the femoral neck ($P = 0.02$) and dominant humerus ($P = 0.02$) compared with controls (Table 1). The other subgroup consisting of ice hockey players was found to have significantly higher BMD at the nondominant humerus ($P = 0.003$) than both the badminton players and controls. There was a significant difference between the dominant and nondominant humerus of 14.8 ± 4.2% for the badminton players ($P < 0.001$), 6.8 ± 6.1% for the control group ($P < 0.001$), but not for the ice hockey players (1.6 ± 6.2%; $P = 0.30$). Using ANOVA, the difference between the dominant and nondominant humerus was significantly greater for

Table 1. Age, antropometric data, physical activity, and bone density of different sites in controls, athletes, and subgroups of athletes at 16 years of age

	Controls (C) (n = 24)	Badminton (B) (n = 12)	Ice hockey (I) (n = 20)	Significance (*P* value)	Athletes (A) (n = 32)	Controls (C) (n = 24)	Significance (*P* value)
Age (yrs)	16.1 ± 0.6	16.1 ± 0.5	16.1 ± 0.5	0.88	16.1 ± 0.5	16.1 ± 0.6	0.65
Weight (kg)	69.2 ± 10.1	65.4 ± 6.1	71.8 ± 7.8	0.13	69.4 ± 7.8	69.2 ± 10.1	0.95
Height (cm)	179 ± 6	177 ± 5	178 ± 5	0.61	178 ± 5	179 ± 6	0.33
Physical activity (hr/w)	1.6 ± 1.2	5.3 ± 1.4	9.4 ± 2.0	$<0.001^{\$}$	7.9 ± 2.7	1.6 ± 1.2	<0.001
Starting age of playing (yrs)		8.7 ± 1.2	7.5 ± 1.8	0.06			
Bone mineral density (g/cm^2)							
Total body	1.15 ± 0.11	1.20 ± 0.05	1.21 ± 0.08	0.10	1.21 ± 0.07	1.15 ± 0.11	0.03
Head	1.91 ± 0.16	1.91 ± 0.10	1.92 ± 0.17	0.95	1.92 ± 0.15	1.91 ± 0.16	0.86
Spine	1.10 ± 0.14	1.14 ± 0.07	1.17 ± 0.08	0.13	1.16 ± 0.08	1.10 ± 0.14	0.06
Humerus (dominant)	1.16 ± 0.14	1.27 ± 0.08	1.24 ± 0.12	$0.02^{£}$	1.25 ± 0.10	1.16 ± 0.14	0.006
Humerus (nondominant)	1.08 ± 0.14	1.10 ± 0.07	1.22 ± 0.10	0.001*	1.18 ± 0.11	1.08 ± 0.14	0.009
Femoral neck	1.13 ± 0.15	1.28 ± 0.13	1.22 ± 0.13	$0.02^{£}$	1.24 ± 0.13	1.13 ± 0.15	0.007
Volumetric bone mineral density (mg/cm^3)							
Femoral neck	405 ± 60	430 ± 50	423 ± 66	0.43	426 ± 59	405 ± 60	0.20
Femoral neck area (cm^2)	5.37 ± 0.49	5.70 ± 0.32	5.54 ± 0.42	0.09	5.60 ± 0.39	5.37 ± 0.49	0.06

Data are presented as means and SD
$^{\$}$I > B > C, $^{£}$B > C, *I > B, C

badminton players than for controls and ice hockey players, and greater for controls compared with ice hockey players ($P < 0.05$).

At the follow-up, at 19 years of age, the athletes had significantly higher BMD at all sites (total body, $P = 0.003$, spine, $P = 0.02$, dominant humerus, $P = 0.001$, nondominant humerus, $P < 0.001$, femoral neck, $P = 0.001$), except for the head ($P = 0.91$) compared with controls (Table 2). The athletes also had higher vBMD at the femoral neck compared with controls ($P = 0.01$). When looking at the subgroups, the badminton players had significantly higher BMD at the dominant humerus ($P = 0.002$) and femoral neck ($P = 0.008$) than both ice hockey players and controls. The ice hockey players had a significantly higher BMD at the total body ($P = 0.01$), spine ($P = 0.04$), dominant humerus ($P = 0.002$), nondominant humerus ($P = 0.001$), and femoral neck ($P = 0.004$) compared with the controls. The ice hockey players also had significantly higher BMD at the nondominant humerus compared with the badminton players ($P = 0.02$). There was still a 13.2 ± 4.7% difference between the dominant and nondominant humerus for the badminton players ($P < 0.001$), 6.5 ± 4.9% for the control group ($P < 0.001$), but not in the ice hockey players (1.3 ± 6.2%; $P = 0.34$). These differences were significantly greater for badminton players than controls and ice hockey players, and greater for controls than for ice hockey players ($P < 0.05$).

The independent predictors of bone density were estimated in the 19-year-old cohort (n = 56) using linear regression (Table 3). Body weight was the strongest independent predictor of all BMD sites ($\beta = 0.39$–0.68; $P < 0.01$). Athletes were found to be independently associated with a higher BMD at all sites ($\beta = 0.26$–0.46; $P < 0.05$) except for head BMD ($\beta = 0.006$; $P = 0.97$).

The increase in bone density between 16 and 19 years of age was analyzed in athletes and controls (Fig. 1). The increase in BMD (g/cm^2) during this period was significant at all sites in both athletes and controls. The athletes as a group (n = 32) increased significantly more at the femoral neck compared with the controls (0.11 vs. 0.07 g/cm^2, $P = 0.04$). The athletes also increased significantly more compared with controls at neck volumetric BMD (24 vs. 1 mg/cm^3, $P = 0.008$). The controls' increase in neck volumetric BMD was not significantly different from zero.

The independent predictors of the change (Δ) in BMD (g/cm^2) of the different sites, between 16 and 19 years of age, were estimated in the athletes and controls using linear regression (Table 4). ΔWeight was found to predict ΔBMD of all sites ($\beta = 0.26$–0.43, $P < 0.05$). ΔHeight independently predicted Δtotal body BMD and BMD of both humeri ($\beta = 0.44$–0.54; $P < 0.01$), and physical activity (h/week) predicted ΔBMD of the nondominant humerus ($\beta = 0.23$; $P < 0.05$). Athletes were found to be independently associated with a higher increase in nondominant humerus BMD ($\beta = 0.24$; $P < 0.05$) and femoral neck BMD ($\beta = 0.30$; $P < 0.05$).

Discussion

The main part of the studies previously evaluating the influence of physical activity on bone accretion is performed on female subjects at different ages [23–25]. It may be difficult to draw any conclusions on how men accrete bone during adolescence and the potential role that physical activity may play in promoting continued

Table 2. Age, antropometric data, physical activity and bone density of different sites in controls, athletes, and subgroups of athletes at 19 years of age

	Controls (C) (n = 24)	Badminton (B) (n = 12)	Ice hockey (I) (n = 20)	Significance (*P* value)	Athletes (A) (n = 32)	Controls (C) (n = 24)	Significance (*P* value)
Age (yrs)	19.1 ± 4	19.1 ± 0.7	19.0 ± 0.4	0.76	19.1 ± 0.5	19.1 ± 0.4	0.51
Weight (kg)	76.8 ± 11.3	73.4 ± 8.7	79.6 ± 9.6	0.26	77.3 ± 9.6	76.8 ± 11.3	0.87
Height (cm)	182 ± 5	180 ± 6	180 ± 5	0.34	180 ± 5	182 ± 5	0.14
Physical activity (hr/w)	3.5 ± 2.2	7.5 ± 2.8	8.7 ± 2.7	$<0.001^{\$}$	8.2 ± 2.7	3.5 ± 2.2	< 0.001
Bone mineral density (g/cm^2)							
Total body	1.26 ± 0.09	1.31 ± 0.05	1.33 ± 0.07	$0.01^{\#}$	1.32 ± 0.07	1.26 ± 0.09	0.003
Head	2.13 ± 0.16	2.11 ± 0.07	2.15 ± 0.15	0.68	2.13 ± 0.12	2.13 ± 0.16	0.91
Spine	1.24 ± 0.14	1.29 ± 0.09	1.34 ± 0.12	$0.04^{\#}$	1.32 ± 0.11	1.24 ± 0.14	0.02
Humerus (dominant)	1.26 ± 0.12	1.39 ± 0.09	1.35 ± 0.12	0.002*	1.37 ± 0.11	1.26 ± 0.12	0.001
Humerus (nondommant)	1.18 ± 0.10	1.23 ± 0.10	1.34 ± 0.09	$0.001^{\pounds}$	1.30 ± 0.11	1.18 ± 0.10	< 0.001
Femoral neck	1.21 ± 0.16	1.37 ± 0.14	1.34 ± 0.15	0.004*	1.35 ± 0.14	1.21 ± 0.16	0.001
Volumetric bone mineral density (mg/cm^3)							
Femoral Neck	406 ± 67	459 ± 43	444 ± 67	0.04	450 ± 59	406 ± 67	0.01
Femoral neck area (cm^2)	5.71 ± 0.50	5.69 ± 0.29	5.82 ± 0.53	0.67	5.77 ± 0.45	5.71 ± 0.50	0.62

Data are presented as means and SD
$^{\$}$I > B,C, $^{\pounds}$I > B > C, *I, B > C, $^{\#}$I > C

Table 3. The independent predictors of all BMD sites (g/cm^2) at 19 years of age in all 56 subjects

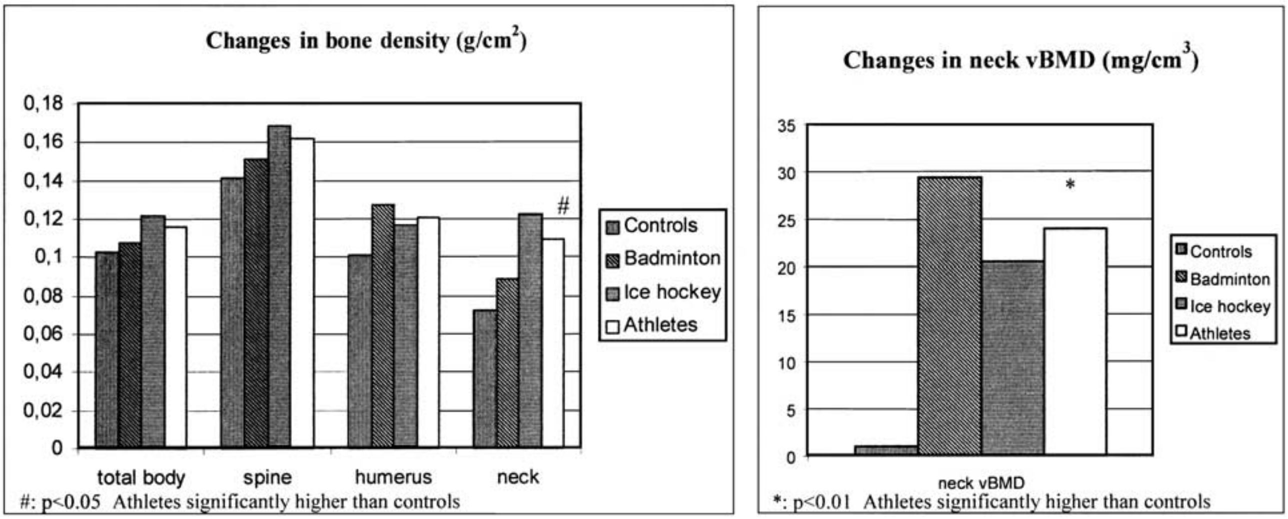
	Bone density					
Independent variables	Total body	Head	Spine	Humerus (dominant)	Humerus (nondominant)	Neck
Athletes > controls	0.36*	0.006	0.26*	$0.43^{\#}$	$0.46^{\pounds}$	$0.40^{\#}$
Body weight (kg)	$0.57^{\#}$	0.29*	$0.68^{\pounds}$	$0.36^{\#}$	$0.51^{\pounds}$	$0.36^{\#}$
Height (cm)	−0.06	−0.08	−0.13	0.006	−0.009	−0.14
Explained variation (R^2)	$0.46^{\pounds}$	0.08	$0.52^{\pounds}$	$0.32^{\pounds}$	$0.48^{\pounds}$	$0.31^{\pounds}$

Regression coefficients and R^2 values are presented
$^{\pounds}$ $P < 0.001$, $^{\#}$ $P < 0.01$, * $P < 0.05$

bone accrual after puberty based on these studies. A study supporting this notion by Sundberg et al. [31] showed that boys age 12–16 exhibit an increased bone accretion with moderate increased physical activity but no increase in bone accretion was noticed in the female cohort of the same age. There have been some studies on the effect of physical activity on BMD in men, cross-sectionally [27], retrospectively [32, 33], longitudinally, [34, 35, 36], as well as controlled trial studies [37], but to our knowledge this is the first longitudinal study on the effect of physical activity on bone accretion just after puberty in adolescent males.

At baseline, the athletes as a whole group had significantly higher BMD of the total body, dominant and nondominant humerus, and femoral neck compared with controls. At the 3-year follow-up, the athletes had significantly higher BMD at all sites except for at the head. Furthermore, to be an athlete was found to be independently associated with a higher increase in nondominant humerus BMD and femoral neck BMD. This increase is probably due to the training pattern in the athlete groups. Both the hockey the badminton training subjected the femoral neck to great stress due to compressive and high tensile forces which probably gives a particular high osteogenic stimulus. Previously, Kannus et al. [38] investigated the association between starting age and differences in bone mass between female tennis and squash players' dominant and nondominant arm. The authors concluded that physical activity should start before puberty to be able to have its maximum effect on bone mass. In our study, the athletes were judged to have passed the pubertal growth spurt period, and still gained significantly more BMD than the controls at some sites. The most important finding of the present study is that bone density of the femoral neck increase also after puberty in males, particularly in subjects exposed to intense physical activity.

One of the subgroups we investigated was ice hockey players. During power skating there are many directional changes, starts, and stops, and players are subjected to gravitational forces, ground reaction forces from the ice through the femur, and compressive forces from the body weight through the acetabulum. Furthermore, high impact forces due to shooting and body contacts, such as tackling, affects the upper body, including the arms [30, 39–41]. Additionally, they trained



#: p<0.05 Athletes significantly higher than controls

*: p<0.01 Athletes significantly higher than controls

Fig. 1. The increases in bone density at different sites in the athletes, subgroups of athletes, and controls during the 3-year study period. Changes in nondominant humerus are presented.

Table 4. The independent predictors of the change (Δ) in BMD (g/cm^2) between 16 and 19 years of age in all 56 subjects were estimated using linear regression

	Bone density site					
Independent variables	ΔTotal body	ΔHead	ΔSpine	ΔHumerus (dominant)	ΔHumerus (nondominant)	ΔFemoral neck
Athlethes > Controls	0.23	−0.03	0.19	0.18	0.24*	0.30*
ΔWeight	$0.36^{\#}$	$0.39^{\#}$	$0.37^{\#}$	0.26*	0.28*	$0.43^{\#}$
ΔHeight	$0.49^{£}$	0.004	0.19	$0.44^{\#}$	$0.54^{£}$	0.21
ΔPhysical activity (hr/w)	0.10	0.004	0.17	0.12	0.23*	0.09
Explained variation (R^2)	$0.4\ 1^{£}$	0.15	$0.24^{\#}$	$0.29^{\#}$	$0.44^{£}$	$0.32^{\#}$

Changes (Δ) in weight, and physical activity, and whether the subject was an athlete or control were used as explanatory variables. Regression coefficients and R^2 values are presented
$^{£}$ $P < 0.001$, $^{\#}$ $P < 0.01$, * $P < 0.05$

in weight-bearing activities such as weight lifting and running, as a complement to their training mainly during the off-season. The ice hockey players exhibited a significantly higher BMD at the nondominant humerus compared with the controls at baseline, and at the 3-year follow-up they also had a significantly higher BMD of the total body, spine, dominant and nondominant humeri, and femoral neck. They also had higher BMD at the nondominant humerus compared with the badminton players. Our results suggest that high impact sports such as ice hockey promote the maintenance of bone density in healthy adolescent males after puberty.

The other subgroup that we investigated was badminton players who were found to have significantly higher BMD than the controls at the dominant humerus and femoral neck at baseline. The same differences between these groups were consistent at 19 years of age except that the badminton players were also found to have a significantly higher volumetric BMD of the femoral neck compared with controls. Our results are in line with what others have found in different racketball sports [42, 43]. Badminton is a sport with short, high impact compressive and tensile forces due to jumps and fast versatile movements and is probably a most effective activity to optimize osteogenesis. Furthermore, the significantly higher differences in BMD when comparing the dominant and nondominant humerus in the subgroup of badminton players compared with controls, implies that badminton may directly influence the local bone formation in the dominant humerus in a positive manner. Our results are supported by others who have shown site-specific differences in BMD associated with selected sports programs [44–46].

Most of the significant differences between the athletes and controls were found when comparing cross-sectional data at 16 and 19 years of age thus, the risk of selection bias is present. However, selection bias could not explain that the difference between dominant and nondominant humerus was greater in the badminton players compared with the controls. Interestingly, the

8% higher difference between the dominant and nondominant humeri when comparing controls and badminton players was about equal to the differences in other BMD sites when comparing the same groups. In the ice-hockey group, where both humeri are subjected to loading during shooting and tackling, there were no significant difference when comparing the dominant and nondominant humerus.

Generally, the bone mass differences when comparing athletes and controls were greatest at sites subjected to high mechanical loading, i.e., the femoral neck and the dominant humerus, suggesting that playing badminton and ice hockey initiates an osteogenic response locally in the bone. The longitudinal component of the study showed that being an athlete was independently related to a higher increase in femoral neck BMD. Furthermore, the controls increased significantly during the study period in BMD of the femoral neck but not in estimated volumetric BMD of the same site. These results suggest that the increase seen in BMD of the femoral neck in the controls is due to changes in size rather than density. The results also suggest that weight-bearing loading is necessary to increase true bone density of the femoral neck after puberty.

It is important to emphasize that this study is not an interventional study; the athletes have trained regularly for many years, and have not changed their lifestyles in any way to fit our study. Still they increased BMD of the femoral neck significantly more than the controls during the study period. One could hypothesize that despite hard training during childhood and adolescence and thereby maximizing the bone mass accretion, their bone is still not saturated. Hence further accretion is possible with adequate amount and type of osteogenic stimuli, at least in males. Our results imply that physical activity has a positive impact on the accrual of bone density especially the clinically important femoral neck even after puberty in our cohort of men.

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