Thicker Radial Cortex in Physically Active Prepubertal Girls Compared to Controls

P. Nanyan
S. Prouteau
C. Jaffré
L. Benhamou
D. Courteix

Abstract

This study was carried out to investigate the effects of physical activity on cortical bone of the radius in a population of prepubertal girls. Forty-nine healthy girls, 17 actives (10.62 ± 1.56 years) and 32 controls (9.84 ± 1.23 years) participated in this study. The active group was involved in gymnastics, judo, and dance on average 7.76 ± 3.94 h/week. Bone mineral content (BMC) and density (BMD) were performed at the distal third of the non-dominant radius using DXA. The lean mass of the non-dominant forearm was derived from the total body analysis performed with DXA. In order to obtain bone cortical thickness, standard radiographs of the non-dominant radius were scanned and computed using a software program based on radiogrammetry. BMD and BMC values were higher in actives than in controls. Cortical thickness at the ulnar side correlated significantly with all the anthropometric and densitometric values as well as the duration of training. In addition, cortical thickness at the ulnar side was significantly higher in the actives compared to the controls. After adjustment for the duration of training per week, cortical thickness of the ulnar side did not differ any more between actives and controls. The same observation was obtained after adjustment for the forearm lean mass. In our active population, physical practice seemed to have induced greater BMC and higher cortical thickness than those observed in the sedentary.

Key words
Radiogrammetry · lean mass · gradient · densitometry · grey level · cortical thickness

Introduction

Impact-loading activities have been shown to have a positive effect on bone mineral acquisition. Dual-energy X-ray absorptiometry (DXA) is currently used in the evaluation of the bone mineral content (BMC) of the human skeleton. But planar DXA measurement is unable to discriminate between trabecular and cortical components of bone known to show specific responses to mechanical strain [33]. Due to this limitation and in order to discriminate the response of each bone compartment, quantitative computed tomography (QCT) and magnetic resonance imaging (MRI) appeared as alternative methods. But QCT and MRI are only available in specialised centres and QCT delivers ionising radiations [7], these points give interest to other techniques such as the radiogrammetry technique [3].

Radiogrammetry has been used for the assessment of bone geometry parameters such as, cortical thickness [3] considered as an indice of bone strength [25]. Thanks to developments in computer sciences, a new digital radiogrammetric method (DXR) has appeared as a reproducible technique [5, 6, 21, 30]. The reproducibility of this DXR was tested on the third distal of the radius shown as a site having increased vulnerability to fractures [18]. It is well accepted that fracture risk can be reduced by means of physical activity, for example by increasing cortical thickness, if started during the growing years [2]. Nevertheless there have

Affiliation
Laboratoire de la Performance Motrice, Orléans University, Equipe Inserm ERIT-M 0101,
Orléans Regional Hospital, Orléans, France

Correspondence
Prof. Daniel Courteix · Laboratoire de la Performance Motrice · Université d'Orléans BP 6237 · 45062 Orléans
Cedex 2 · France · E-mail: Daniel.courteix@univ-orleans.fr

Accepted after revision: January 12, 2004

Bibliography
Int J Sports Med 2005; 26: 110 – 115 © Georg Thieme Verlag KG · Stuttgart · New York ·
DOI 10.1055/s-2004-817859 · Published online July 30, 2004 ·
ISSN 0172-4622

been very few investigations in children regarding the association between cortical thickness and physical activity. In fact the prepubertal years are an opportune period for the bone modelling and remodelling processes in response to mechanical loading [2,29]. This study was therefore carried out to study the bone geometry parameters in a population of prepubertal girls, taking into account the effects of physical activity.

Subjects and Methods

Subjects

Forty-nine healthy girls, 17 actives (10.62 ± 1.56 years) and 32 controls (9.84 ± 1.23 years) participated in this study (Table **1**). The active group, in addition to the school physical education course, participated in activities such as gymnastics and judo on average 7.61 ± 3.76 h/week in their club. The control group was engaged only in physical education course and recreational activities (non formal games e.g street basket) for no more than 3 h/week. These activities did not involve any heavy loading or impact that could have biased the study.

Our regional Ethics Committee approved the study, and written informed consent was obtained from the children and their parents.

Anthropometric determinations

All the subjects were healthy and had never used medication known to affect bone properties. Body weight and height were measured in all subjects.

Bone age was assessed by left hand and wrist radiographs and analysed following the method of Greulich and Pyle [11], to insure that there was no pathological retardation or acceleration in bone maturity. Their puberty stage was determined according to Tanner's criteria [27].

The lean mass (LM, kg) of the non-dominant forearm, as representative of the muscular mass, was determined from the total body regional analysis on DXA using the software supplied by the manufacturer (Hologic QDR 4500/W; Hologic, Waltham, MA, USA).

Bone mineral measurements

Bone mineral content (BMC, g) and density (BMD, g/cm^2) were performed using DXA. Measurements were made at the total body and at the distal third of the non-dominant radius (Fig. **1**). The reproducibility of the technique was based on two repeated measurements over two weeks in three subjects. The *in vivo* coefficient of variation (CV) was less than 0.9% at the whole body and 1.2% at the radius in our laboratory.

Bone cortical measurements by radiogrammetry

One radiograph of the non-dominant forearm was obtained for each subject using a standard procedure. The forearm was placed in contact with the film using a focal-forearm distance settled at 1 m. The same X-ray tube, voltage (48 kV), and exposure conditions (18 mAs for 0.08 s) were used. The effective dose radiation was 0.13 µSv.

Table **1** Anthropometric data and age of the subjects

Parameter	*Actives* *n = 17* *(gymnastics = 14* *judo = 3)*	*Controls* *n = 32*	*Difference*
Chronological age (yrs)	10.62 ± 1.56	9.84 ± 1.23	ns
Bone age (yrs)	10.40 ± 2.09	9.84 ± 1.31	ns
Height (cm)	141.41 ± 8.64	137.2 ± 8.71	ns
Weight (kg)	32.92 ± 6.40	30.36 ± 6.48	ns
Years of training	4.6 ± 1.8		

ns: not significant

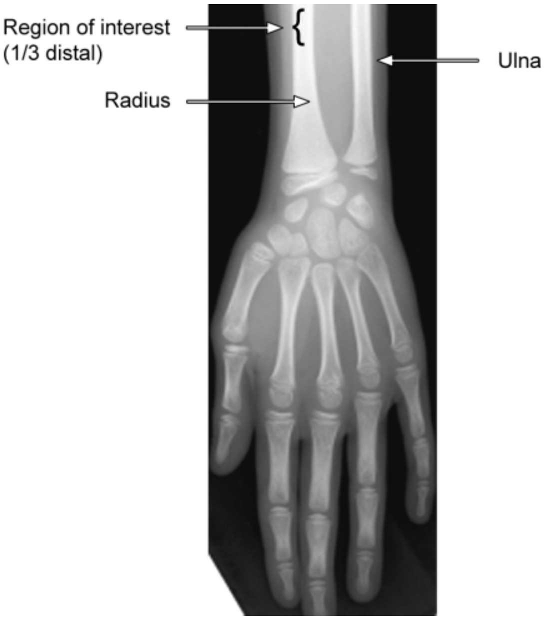

Fig. **1** Selection of the radius from the radiograph.

On the radiographs, the radius was selected and digitised with a high-resolution scanner (100 µm resolution at a 8 bits pixel greyscale). The resulting digitised images (Fig. **1**) were transferred to a UNIX workstation. Our program, on the first step, extracted the bone edge using the Deriche's filter based on the gradient magnitude. On the second step, to separate the cortical and the trabecular areas, we applied an automatic thresholding approach based on the iterative contour detection method using the grey level peak. The entire procedure has been described elsewhere [30]. Thus, the mean cortical thicknesses on the radial and ulnar sides could be determined on 15 lines on both sides of a reference line drawn automatically by our home-made program [30] at the third distal of the radius (Fig. **2**). The root mean square coefficient of variation [22] of the technique was 1.36% in this study.

Statistical analyses

The mean and standard deviations were calculated for all anthropometric data, values issued from the analysis of radiographs and bone measurements. All data were compared between the active and control subjects using a Student's *t*-test. A *t*-paired

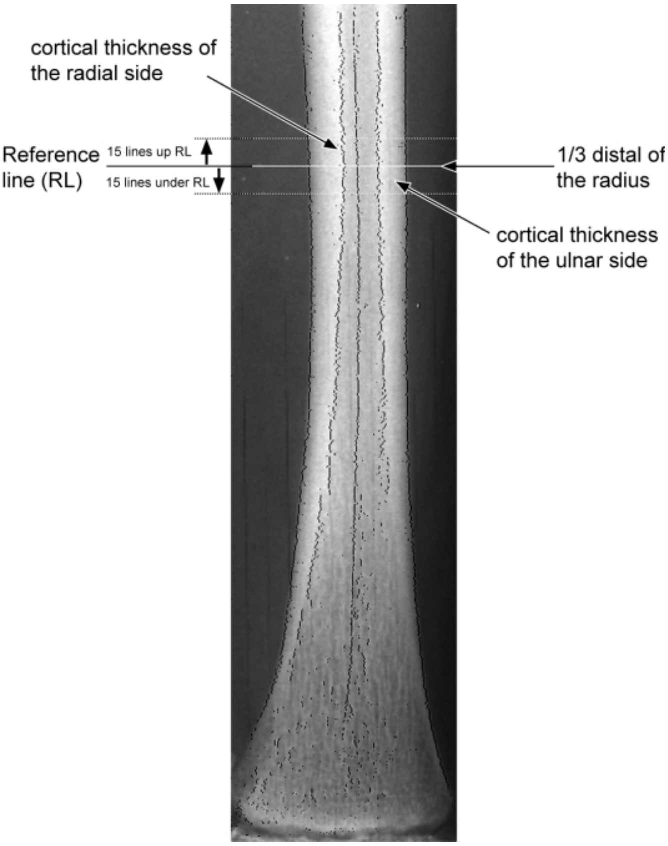

Fig. **2** Image of the radius after the process showing the cortical thicknesses on the ulnar side and on the radial side.

test was used to assess the potential differences between cortical thickness at the ulnar and radial sides. Radiogrammetric data were also adjusted using analysis of covariance with duration of training and forearm lean mass as covariates. The relationships between radiogrammetric, anthropometric, and bone measurements were examined using Pearson's correlation test with a limit of significance at $p < 0.05$.

Results

Anthropometric, age, and densitometric determinations

Physical characteristics for actives and controls are given in Table **1**. There was no significant difference between groups as regards chronological age, bone age, height, and weight.

Significant differences ($p < 0.05$) were observed between actives and controls for the duration of training per week and densitometric values both at the non-dominant forearm and at the distal third of the non-dominant radius (Table **2**).

Radiogrammetric analyses

There was no significant difference between cortical thicknesses at the ulnar and the radial side (3.13 vs. 3.07 mm, respectively) in all subjects as well as in actives and controls. But as shown in Table **2**, cortical thickness at the ulnar side was significantly greater in the actives compared to the controls. After adjustment for the duration of training per week, cortical thickness at the ulnar side did not any more differ significantly ($p < 0.05$) between actives and controls (3.24 vs. 3.12 mm, respectively). There was also no difference when the cortical thickness at the ulnar side was adjusted for the forearm lean mass (3.46 vs. 2.99 mm).

Correlation between anthropometric, radiogrammetric, and densitometric data

As shown in Table **3**, the anthropometric values correlated significantly with cortical thickness at the ulnar side and cortical thickness for both sides in all the subjects. Maturation explained 27% of the variance in cortical thickness at the ulnar side.

A significant correlation was obtained between the duration of training per week and cortical thickness of both sides ($r = 0.34$, $p < 0.05$), cortical thickness at the ulnar side ($r = 0.41$, $p < 0.01$) (Table **3**) as well as with the non-dominant forearm lean mass ($r = 0.44$, $p < 0.01$).

Table **2** Comparison between actives and controls

Parameter	*Actives n = 17 (gymnastics = 14 judo = 3)*	*Controls n = 32*	*Difference 95% CI*	*Significance*
Cortical thickness				
– *radial side (mm)*	3.18 ± 0.87	3.03 ± 0.95	– 0.46; 0.72	ns
– *ulnar side (mm)*	3.47 ± 0.75	3.00 ± 0.44	0.11; 0.8	**
Non-dominant forearm				
– *lean mass (g)*	586.91 ± 104.63	512.82 ± 103.91	9.11; 139.8	*
– *BMC (g)*	22.84 ± 7.71	16.76 ± 5.72	2.11; 10.05	**
– *BMD (g/cm²)*	0.60 ± 0.05	0.55 ± 0.05	0.01; 0.07	**
Third distal of the radius				
– *BMC*	1.18 ± 0.21	0.97 ± 0.12	0.10; 0.30	***
– *BMD*	0.51 ± 0.05	0.48 ± 0.03	0.05; 0.059	*
Duration of training per week (h/w)	7.82 ± 3.77	1.21 ± 1.13	5.17; 8.05	***

CI: Confidence interval; * < 0.05; ** < 0.01; *** < 0.001; ns: not significant; BMC: bone mineral content; BMD: bone mineral density

Table **3** Correlation between anthropometric, age, densitometric, and radiogrammetric measurements in all subjects

Parameter	*Cortical thickness of the radial side*	*Cortical thickness of the ulnar side*	*Both sides*
Chronological age	0.44**	0.47***	0.59***
Bone age	0.27	0.49***	0.45***
Height	0.37**	0.43**	0.49***
Weight	0.27	0.40**	0.43**
Non-dominant forearm lean mass	0.47***	0.44**	0.60***
Duration of training per week	0.21	0.41**	0.34*
Distal third of the radius			
– *BMC*	0.52***	0.77***	0.76***
– *BMD*	0.34*	0.48***	0.56***
Non-dominant forearm			
– *BMC*	0.55***	0.52***	0.69***
– *BMD*	0.35**	0.46***	0.51***

* < 0.05; ** < 0.01; *** < 0.001; BMC: bone mineral content; BMD: bone mineral density

Table **4** Comparison of the accuracy of the measurements at the third distal of the radius

Authors	*Technique*	*Cortical thickness (mm)*	*Age of the subjects (yrs)*
Louis et al. [26]	pQCT	1.93 – 3.09^{T} 2.3 – 2.94^{I}	61 – 85
Haapasalo et al. [13]	pQCT	3.36^{T}# 3.1 – 3.6^{T}	30 ± 5
Kardinaal et al. [23]	DXA	1.7 – 2.2	Tanner 1
Lochmüller et al. [25]	pQCT	1.9 – 2.8^{T}	46 – 97
Our study	DXR	2.26 – 4.22^{I}# 2.08 – 3.98^{I}	Tanner 0 – 1

^{T} threshold algorithm; ^{I} iterative contour detection; # trained subjects; Tanner: Tanner stage

The radiogrammetric values correlated significantly with all the densitometric data (Table **3**).

The duration of training per week, bone age, and body weight were entered into a multiple regression analysis. The most predictable parameter for cortical thickness at the ulnar side was duration of training per week (F = 5.32, p = 0.02).

Discussion

The main finding of the present study was that impact-loading training was accompanied by a higher value in the cortical thickness of the radius.

In accordance with our results, previous studies have shown a gain in cortical thickness in femur of rat [16,17,19,20,32,36,38] as well as in femur [1,3,7,8], humerus [14,24], radius [13], and metacarpal [3] in human, in response to impact loading constraints. In the present study, active subjects had higher cortical thickness at the ulnar side than controls. In fact, such an osteogenic effect on the active group was expected since the activities included high-impact loading sports such as gymnastics and judo [4,28].

Actives and controls differed only for cortical thickness at the ulnar side and such a difference could probably be explained by the muscle attachments that act on the bone [9] or/and the variety of strains undergone by the bone [12,37]. Regarding the first point, the muscular actions are more predominant on the ulnar side of the radius than on its radial side [31]. These actions might have influenced the accumulation of bone mass more on the ulnar side. Also in this study, the non-dominant forearm lean mass correlated significantly with the cortical thickness suggesting thus the predominance of the mechanical effect [10].

The second point stresses that the remodelling response to strain varies depending on the loading conditions [12,37]. Gross et al. [12] demonstrated that during complex loading conditions involving bending, axial compression, and torsion, as during specific sport activities, the strain distributions across the cortex are not uniform.

Several authors have used DXA [23] or peripheral quantitative computed tomography (pQCT) [13,25,26] in subjects of various age, to measure cortical thickness at the distal third of the radius. The use of different methods makes the comparisons between studies difficult (Table **4**). However, the cortical thickness values obtained with our technique (DXR) were similar to those reported by Haapasalo et al. [13] in adult subjects using pQCT. But the absolute cortical thickness values might not be accurately measurable due to the limited spatial resolution (0.2 – 0.6 mm) of the pQCT system [15,34] and the use of the threshold algorithm method (to separate cortical bone from marrow cavity) [26]. It was possible, in our study, to measure the cortical thickness of the radius to the nearest 0.1 mm, based on the true shape of the bone, without making any geometrical assumption [26].

The values reported by Kardinaal et al. [23] (1.92 – 2.25 mm) in prepubertal children using DXA were 22 – 80% lower than ours (2.08 – 4.22 mm). This difference seems to be due to inaccurate measurements of the cortical thickness using DXA [39] with the underestimation values reaching 64.8% [35].

The most critical point of the present study was the estimation of the three-dimensional geometry on the basis of the two-dimensional radiographic measurements. Even if the distance between the roentgen radiation and the film is uniform, the bone projection is magnified depending on the size of the forearm. Therefore, the cortical thickness is size-dependent. But the data obtained, due to good reproducibility of the measurements, may insure that the technique is able to give results considered as valid. The only practical valid solution, to avoid this size effect, would be the use of the MRI or pQCT to measure the bone in a three-dimensional manner [35]. Due to their cost and limited availability now, these methods might be widely used in the future. For all the subjects, the lack of difference between cortical thicknesses at the radial and ulnar sides, indicates a trend to symmetry in the cortical thickness between the radial and ulnar sides of the radius. This result seems accurate since the subject's forearm was positioned by the same trained technician according to a standard fixed protocol, thus controlling rotation, parallax, and exposure [9].

In our study, although maturation of the subjects explained 27% of the variance in cortical thickness at the ulnar side, the best predictor for the cortical thickness at the ulnar side was duration of training per week. Also, the difference in cortical thickness at the ulnar side between actives and controls disappeared when adjusted for duration of training. As in our study, there were no differences in chronological age, bone age, height, and weight between active and control subjects, the difference observed in bone geometry was more likely associated with the impact-loading inherent to sport activities.

In conclusion, our findings suggest that, in prepubertal girls, high-impact sports such as gymnastics and judo might result in greater cortical thickness that gives the bone more resistance and thus prevents bone fractures later in life.

Acknowledgement

The data were presented in part at the 2nd Congress of Exercise Physiology in Children, Orléans, France, November 2002.

References

1. Bass S, Pearce G, Bradney M, Hendrich E, Delmas PD, Harding A, Seeman E. Exercise before puberty may confer residual benefits in bone density in adulthood: studies in active prepubertal and retired female gymnasts. J Bone Miner Res 1998; 13: 500 – 507
2. Bass SL, Saxon L, Daly RM, Turner CH, Robling AG, Seeman E, Stuckey S. The effect of mechanical loading on the size and shape of bone in pre-, peri-, and postpubertal girls: a study in tennis players. J Bone Miner Res 2002; 17: 2274 – 2280
3. Bradney M, Pearce G, Naughton G, Sullivan C, Bass S, Beck T, Carlson J, Seeman E. 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 1998; 13: 1814 – 1821
4. Courteix D, Lespessailles E, Peres SL, Obert P, Germain P, Benhamou CL. Effect of physical training on bone mineral density in prepubertal girls: a comparative study between impact-loading and non-impact-loading sports. Osteoporos Int 1998; 8: 152 – 158
5. Crespo R, Revilla M, Usabiago J, Crespo E, Garcia-Arino J, Villa LF, Rico H. Metacarpal radiogrammetry by computed radiography in postmenopausal women with Colles' fracture and vertebral crush fracture syndrome. Calcif Tissue Int 1998; 62: 470 – 473
6. Derisquebourg T, Dubois P, Devogelaer JP, Meys E, Duquesnoy B, Nagant de Deuxchaisnes C, Delcambre B, Marchandise X. Automated computerized radiogrammetry of the second metacarpal and its correlation with absorptiometry of the forearm and spine. Calcif Tissue Int 1994; 54: 461 – 465
7. Duncan CS, Blimkie CJ, Kemp A, Higgs W, Cowell CT, Woodhead H, Briody JN, Howman-Giles R. Mid-femur geometry and biomechanical properties in 15- to 18-yr-old female athletes. Med Sci Sports Exerc 2002; 34: 673 – 681
8. Faulkner RA, Forwood MR, Beck TJ, Mafukidze JC, Russell K, Wallace W. Strength indices of the proximal femur and shaft in prepubertal female gymnasts. Med Sci Sports Exerc 2003; 35: 513 – 518
9. Fox KM, Kimura S, Powell-Threets K, Plato CC. Radial and ulnar cortical thickness of the second metacarpal. J Bone Miner Res 1995; 10: 1930 – 1934
10. Frost HM. Muscle, bone, and the Utah paradigm: a 1999 overview. Med Sci Sports Exerc 2000; 32: 911 – 917
11. Greulich WW, Pyle SI. Radiographics Atlas of Skeletal Development of Hand and Wrist. 2nd ed. Standford: Standford University Press, 1959
12. Gross TS, McLeod KJ, Rubin CT. Characterizing bone strain distributions in vivo using three triple rosette strain gages. J Biomech 1992; 25: 1081 – 1087
13. Haapasalo H, Kontulainen S, Sievanen H, Kannus P, Jarvinen M, Vuori I. 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 2000; 27: 351 – 357
14. Haapasalo H, Sievanen H, Kannus P, Heinonen A, Oja P, Vuori I. Dimensions and estimated mechanical characteristics of the humerus after long-term tennis loading. J Bone Miner Res 1996; 11: 864 – 872
15. Hangartner TN, Gilsanz V: Evaluation of cortical bone by computed tomography. J Bone Miner Res 1996; 11: 1518 – 1525
16. Hsieh YF, Robling AG, Ambrosius WT, Burr DB, Turner CH. Mechanical loading of diaphyseal bone in vivo: the strain threshold for an osteogenic response varies with location. J Bone Miner Res 2001; 16: 2291 – 2297
17. Hsieh YF, Turner CH. Effects of loading frequency on mechanically induced bone formation. J Bone Miner Res 2001; 16: 918 – 924
18. Hsu ES, Patwardhan AG, Meade KP, Light TR, Martin WR. Cross-sectional geometrical properties and bone mineral contents of the human radius and ulna. J Biomech 1993; 26: 1307 – 1318
19. Iwamoto J, Yeh JK, Aloia JF. Effect of deconditioning on cortical and cancellous bone growth in the exercise trained young rats. J Bone Miner Res 2000; 15: 1842 – 1849
20. Jarvinen TL, Kannus P, Sievanen H, Jolma P, Heinonen A, Jarvinen M. Randomized controlled study of effects of sudden impact loading on rat femur. J Bone Miner Res 1998; 13: 1475 – 1482
21. Kalla AA, Meyers OL, Parkyn ND, Kotze TJ. Osteoporosis screening – radiogrammetry revisited. Br J Rheumatol 1989; 28: 511 – 517
22. Kannus P, Haapasalo H, Sankelo M, Sievanen H, Pasanen M, Heinonen A, Oja P, Vuori I. Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. Ann Intern Med 1995; 123: 27 – 31
23. Kardinaal AF, Hoorneman G, Vaananen K, Charles P, Ando S, Maggiolini M, Charzewska J, Rotily M, Deloraine A, Heikkinen J, Juvin R, Schaafsma G. Determinants of bone mass and bone geometry in adolescent and young adult women. Calcif Tissue Int 2000; 66: 81 – 89
24. Kontulainen S, Sievanen H, Kannus P, Pasanen M, Vuori I. Effect of long-term impact-loading on mass, size, and estimated strength of humerus and radius of female racquet-sports players: a peripheral quantitative computed tomography study between young and old starters and controls. J Bone Miner Res 2003; 18: 352 – 359
25. Lochmuller EM, Groll O, Kuhn V, Eckstein F. Mechanical strength of the proximal femur as predicted from geometric and densitometric bone properties at the lower limb versus the distal radius. Bone 2002; 30: 207 – 216
26. Louis O, Willnecker J, Soykens S, Van den Winkel P, Osteaux M. Cortical thickness assessed by peripheral quantitative computed tomography: accuracy evaluated on radius specimens. Osteoporos Int 1995; 5: 446 – 449
27. Marshall WA, Tanner JM. Variation in pattern of pubertal changes in girls. Arch Dis Child 1969; 44: 291 – 303
28. Matsumoto T, Nakagawa S, Nishida S, Hirota R. Bone density and bone metabolic markers in active collegiate athletes: findings in long-distance runners, judoists, and swimmers. Int J Sports Med 1997; 18: 408 – 412
29. Morris FL, Naughton GA, Gibbs JL, Carlson JS, Wark JD: Prospective ten-month exercise intervention in premenarcheal girls: positive effects on bone and lean mass. J Bone Miner Res 1997; 12: 1453 – 1462

[30] Nanyan P, Pothuaud L, Benhamou L, Courteix D. Semi-automated evaluation of the cortico-medullar index on radius radiographs: a study in prepubertal girls. Eur J Radiol 2003; 47: 47 – 53

[31] Netter FH. Atlas d'Anatomie Humaine. 2nd ed. New Jersey, USA: Masson, 1997; 420 – 421

[32] Rubin C, Turner AS, Bain S, Mallinckrodt C, McLeod K. Anabolism. Low mechanical signals strengthen long bones. Nature 2001; 412: 603 – 604

[33] Rubin C, Turner AS, Mallinckrodt C, Jerome C, McLeod K, Bain S. Mechanical strain, induced noninvasively in the high-frequency domain, is anabolic to cancellous bone, but not cortical bone. Bone 2002; 30: 445 – 452

[34] Schmidt C, Priemel M, Kohler T, Weusten A, Muller R, Amling M, Eckstein F. Precision and accuracy of peripheral quantitative computed tomography (pQCT) in the mouse skeleton compared with histology and microcomputed tomography (microCT). J Bone Miner Res 2003; 18: 1486 – 1496

[35] Sievanen H, Kannus P, Nieminen V, Heinonen A, Oja P, Vuori I. Estimation of various mechanical characteristics of human bones using dual energy X-ray absorptiometry: methodology and precision. Bone 1996; 18: 17 S – 27 S

[36] Singh R, Umemura Y, Honda A, Nagasawa S. Maintenance of bone mass and mechanical properties after short-term cessation of high impact exercise in rats. Int J Sports Med 2002; 23: 77 – 81

[37] Turner CH, Forwood MR, Rho JY, Yoshikawa T. Mechanical loading thresholds for lamellar and woven bone formation. J Bone Miner Res 1994; 9: 87 – 97

[38] Umemura Y, Ishiko T, Yamauchi T, Kurono M, Mashiko S. Five jumps per day increase bone mass and breaking force in rats. J Bone Miner Res 1997; 12: 1480 – 1485

[39] Woodhead HJ, Kemp AF, Blimkie CJR, Briody JN, Duncan CS, Thompson M, Lam A, Howman-Giles R, Cowell CT. Measurement of midfemoral shaft geometry: repeatability and accuracy using magnetic resonance imaging and dual-energy X-ray absorptiometry. J Bone Miner Res 2001; 16: 2251 – 2259