Effects of physical training on cortical bone at midtibia assessed by peripheral QCT

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BONE MINERAL DENSITY (BMD) measurement is very important in clinical management of osteoporosis, because bone density reduction closely correlates to an increased fracture rate (7, 13, 18, 20, 27). Commonly used methods to evaluate BMD are single-photon absorptiometry, dual-photon absorptiometry, dual-energy X-ray absorptiometry (DXA), and peripheral quantitative computed tomography (pQCT) (2, 12). In contrast to single-photon absorptiometry, dual-photon absorptiometry, and DXA, pQCT measures volumetric BMD (vBMD; in g/cm³) and allows for separate assessment of trabecular and cortical bone of the appendicular skeleton, such as the radius and tibia (12, 37, 38). Furthermore, pQCT, a new generation of bone densitometry technique, can determine bone geometric properties, which are closely related to bone strength, in addition to vBMD (9, 24, 32, 33, 41).

The positive effect of physical activity on human bone mass has been well documented in many cross-sectional studies comparing athletes with sedentary controls (3, 8, 11, 14, 16, 17, 21, 23, 29, 42, 43). One of the early studies using DXA of adolescent athletes reported enhanced areal BMD (aBMD) of distal femur (29) and whole body in athletes (11, 43). Furthermore, comparison of aBMD among athletes revealed the importance of impact loading to increase aBMD. Young female athletes who engage in impact loading sports, such as volleyball and gymnastics, have a greater aBMD at a majority of skeletal sites, compared with controls and athletes in an active loading sport, such as swimming, in which loading occurs through muscle strain (6, 11, 26, 43). On the other hand, a previous study assessed the effect of physical activity on the side-to-side differences of tennis players’ radii using pQCT and showed that tennis playing led to a slight decrease in cortical vBMD but increase in both periosteal and endocortical bone area at midradius (1). It revealed that an improvement of the mechanical properties of young adult bone in response to long-term exercise is related to geometric adaptation and not to vBMD.
Table 1. Characteristics of male and female swimmers, jumpers, and controls

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>Swimmers</th>
<th>Jumpers</th>
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<tr>
<td>Men</td>
<td></td>
<td></td>
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<tr>
<td>Age, yr</td>
<td>20.3 ± 1.6</td>
<td>19.5 ± 0.7</td>
<td>19.8 ± 1.3</td>
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<tr>
<td>Height, cm</td>
<td>176.1 ± 4.1</td>
<td>176.3 ± 4.5</td>
<td>178.2 ± 6.0</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>67.3 ± 10.6</td>
<td>72.3 ± 4.9*</td>
<td>67.2 ± 3.7†</td>
</tr>
<tr>
<td>Age at start of training, yr</td>
<td>9.8 ± 1.9</td>
<td>12.8 ± 2.1†</td>
<td>5.0 ± 0.0†</td>
</tr>
<tr>
<td>Training sessions per week, days</td>
<td>6.0 ± 0.0</td>
<td>5.0 ± 0.0†</td>
<td>12.1 ± 0.8</td>
</tr>
<tr>
<td>Menarche, yr</td>
<td>11.9 ± 1.4</td>
<td>12.9 ± 1.4</td>
<td>11.0 ± 3.2</td>
</tr>
<tr>
<td>Menstrual cycles per year</td>
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Values are mean ± SD; n, no. of subjects. Significant difference: * vs. control [multiple comparison by Fisher’s protected least significant difference (PLSD), P < 0.05]; † vs. swimmers (multiple comparison by PLSD, P < 0.05).

long-term exercise on vBMD, geometric properties, and the bone strength indexes of jumpers as a high-impact loading group and swimmers as a nonimpact and active loading group, compared with nonathletic controls, by using pQCT.

MATERIALS AND METHODS

Subjects. A study population comprising 37 male adults (10 controls, 15 swimmers, and 12 jumpers) and 43 female adults (15 controls, 15 swimmers, and 13 jumpers), aged 18–23 yr, was recruited from the University of Tsukuba, Japan. The jumpers, including long-jump, high-jump, triple-jump, and pole-jump athletes, and the swimmers, including backstroke, breaststroke, butterfly stroke, and freestyle swimming athletes, were active top level. The controls consisted of gender- and age-matched sedentary nonathletes. Training history, age at training onset, and condition of menorrhrea (female participants were asked to recall the menarche age and the menstrual cycles over the past year) were investigated by direct interview. The exercise, smoking, and alcohol use habits and medical history were obtained through questionnaires. The subjects were clinically healthy, and none had any disease, took medication affecting bone metabolism, or had had tibial fractures, except for one jumper, who had had a left tibial fracture. Group characteristics are given in Table 1. Written, informed consent was obtained before the study, and the project was approved by the University of Tsukuba Human Subjects Institutional Review Board.

Bone measurement. The midtibia of the nondominant limb was measured by using pQCT (Densiscan1000, Scanco Medical, Zurich, Switzerland), with an effective X-ray energy of 40 keV. The nondominant leg was positioned in a radiolucent cast anatomically suitable for the subject during computed tomography scanning. After an anterior-posterior projection scout view was displayed, a reference line was set at the right angle to the long axis of the lower limb and placed on the middle point of the end-plate of the distal tibia. A slice 66 mm proximal from the reference line was analyzed, according to the manufacturer’s suggestion for cortical bone assessment. The thickness of one slice was 1 mm, and a voxel size was 0.355 × 0.355 mm. A standard phantom measurement was performed daily, which resulted in a long-term reproducibility of 0.3%, as vBMD was measured in adults of various age groups of both genders (35, 36).

Data analysis. The pQCT bone image was transmitted to a Macintosh computer in custom mode (resolution: 256 × 256 pixels) and imported into NIH Image [version 1.61, Wayne Rasband, National Institutes of Health (NIH)] to analyze vBMD, bone mineral content (BMC), and geometric properties. The cortical bone was defined as that with a volumetric density of >0.7 g/cm³ (44). Endocortical and periosteal areas were defined as cross-sectional areas surrounded by the inner and outer surface of the cortical bone, respectively. Cortical area was defined by the difference between periosteal and endocortical areas. Cortical thickness was defined as the mean distance between the inner and outer edge of the cortical shell. BMC was defined as the mineral content of the bone within a 1-mm slice (g/mm). Coefficients of variation for triplicate measurements of three human subjects after repositioning were 0.10–0.72% for vBMD, 0.44–0.74% for bone area, and 0.79% for cortical thickness. The polar moment of inertia and strength strain index (SSI) were calculated as the measure of the strength indexes of bone (39). Figure 1 shows an inverse image of the tibia on NIH image software.

Statistical analysis. Values are presented as means ± SD. Group differences in descriptive data were evaluated by using ANOVA for men and women separately. Fisher’s post hoc test analysis was performed for the significant values in ANOVA, and a correlation was also run between vBMD and bone geometric properties.

Fig. 1. Calculation of polar moment of inertia and strength strain index (SSI). A Densiscan image of the tibia was imported into NIH Image to analyze the volumetric bone mineral density (vBMD), bone mineral content (BMC), geometric properties, and strength indexes of the bone. This example is an inverse image of a tibia on NIH Image software. Cortical bone was defined as that with a volumetric density of >0.7 g/cm³, and the strength indexes were calculated as follows (39): polar moment of inertia (mm²) = \( I = \sum(d^2 \times A) \) and SSI (mm³) = \( \sum(d^2 \times A \times \text{vBMD}_{\text{vox}}/\text{vBMD}_{\text{max}}) / d_{\text{max}} \), where \( d \) is the distance (mm) of the voxel from the center of gravity (C), \( A \) is the cross-sectional area of a voxel (in this study it is 0.076 mm²), \( \text{vBMD}_{\text{vox}} \) is the vBMD in the voxel (mg/mm³), \( \text{vBMD}_{\text{max}} \) is the maximum vBMD (mg/mm³), and \( d_{\text{max}} \) is the maximum distance of any of the voxels of the cortical cross section from the center of gravity (mm).
RESULTS

Physical characteristics of the subjects. The physical characteristics of the groups are given in Table 1. There was no significant difference in height among the male groups, whereas swimmers were significantly heavier than the other groups. The male athletes were significantly taller and heavier than the controls, although there were no significant differences between swimmers and jumpers. The starting age of training was earlier and the training duration was longer for swimmers and jumpers. The age of menarche and the number of menstrual cycles during the past 12 mo were similar among the three female groups.

Bone measurement. There were no differences in vBMD of whole and cortical bone among the three male groups. In the women, the whole vBMD of the swimmers was 13.2 and 13.8% lower than that of controls and jumpers, and the cortical vBMD of swimmers and jumpers was 5.0 and 4.0% lower, respectively, than that of the controls. The cortical BMC of the male jumpers was 8.0 and 10.2% greater than that of the controls and swimmers, and that of female jumpers was 30.6 and 27.0% greater, respectively, than that of controls and swimmers. The periosteal areas of male jumpers, female swimmers, and female jumpers were 11.4, 20.3, and 33.5%, respectively, greater than that of controls. The endocortical area of female swimmers was 43.5% greater than that of controls. The cortical area of jumpers was greater than that of controls (10.2% in men and 34.8% in women) and swimmers (11.1% in men and 26.0% in women). The cortical thickness of jumpers was thicker than that of swimmers (9.6% in men and 25.0% in women), and the female jumpers’ cortical thickness was also 18.2% thicker than that of the controls. The polar moment of inertia of male jumpers was 22.4% greater than that of controls, and that of female swimmers and female jumpers was 47.7 and 95.4% greater, respectively, than that of controls. Compared with swimmers, the polar moment of inertia of jumpers was 15.1% greater in men and 32.3% greater in women. SSI of female swimmers and jumpers were 51.5 and 82.1%, respectively, greater than that of controls. By ANCOVA, it was suggested that the body size (height and weight) influenced the cortical area in men and cortical thickness in both men and women significantly. However, statistical differences among group means remained unchanged after size-adjusted analysis (Table 2).

Correlation. Periosteal and endocortical areas were negatively correlated with cortical vBMD in both genders (Fig. 2).

DISCUSSION

pQCT allows estimation of true BMD, i.e., vBMD in grams per cubic centimeter, and the geometric properties of the bone (12, 37, 38). Studies concerning the effect of physical training on bone using pQCT are scarce, with a few studies analyzing the side-to-side difference in tennis players’ arms (1, 15, 28), a limited number on jumpers’ legs (19), and a study on volleyball players’ lower legs (34).

The present study evaluated vBMD, BMC, geometric properties, and the strength indexes of the tibia of male and female jumpers as a typical example of bone exposed to an extremely high-impact mechanical load. The periosteal area, cortical area, and polar moment of inertia were greater in male and female jumpers than in controls. The results showed the significant wider periosteal area (drift toward periosteal direction) and not a greater vBMD in jumpers’ tibiae, confirming the conclusions of previous studies in young subjects (1, 15, 19) that improvement of the mechanical properties of bone in response to long-term physical exercise is re-

Table 2. pQCT parameters of male and female participants’ tibia

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<tr>
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<tr>
<td>n</td>
<td>10</td>
<td>15</td>
<td>12</td>
<td>15</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Whole BMD, g/cm³</td>
<td>1.15 ± 0.12</td>
<td>1.08 ± 0.13</td>
<td>1.13 ± 0.13</td>
<td>1.29 ± 0.18</td>
<td>1.12 ± 0.16†</td>
<td>1.30 ± 0.22†</td>
</tr>
<tr>
<td>Cortical BMD, g/cm³</td>
<td>1.81 ± 0.10</td>
<td>1.79 ± 0.09</td>
<td>1.79 ± 0.06</td>
<td>2.00 ± 0.05</td>
<td>1.90 ± 0.08†</td>
<td>1.92 ± 0.13†</td>
</tr>
<tr>
<td>Cortical BMC, g/mm²</td>
<td>0.50 ± 0.31</td>
<td>0.48 ± 0.04</td>
<td>0.54 ± 0.04†</td>
<td>0.36 ± 0.07</td>
<td>0.37 ± 0.04</td>
<td>0.47 ± 0.03††</td>
</tr>
<tr>
<td>Periosteal area, mm²</td>
<td>460 ± 50</td>
<td>483 ± 46</td>
<td>512 ± 55*</td>
<td>283 ± 52</td>
<td>341 ± 73*</td>
<td>378 ± 75*</td>
</tr>
<tr>
<td>Endocortical area, mm²</td>
<td>185 ± 39</td>
<td>210 ± 42</td>
<td>209 ± 54</td>
<td>103 ± 29</td>
<td>148 ± 52*</td>
<td>135 ± 54</td>
</tr>
<tr>
<td>Cortical area, mm²</td>
<td>275 ± 21</td>
<td>273 ± 22</td>
<td>303 ± 24††</td>
<td>180 ± 36</td>
<td>193 ± 25</td>
<td>243 ± 24††</td>
</tr>
<tr>
<td>Cortical thickness, mm</td>
<td>4.46 ± 0.29</td>
<td>4.25 ± 0.44</td>
<td>4.66 ± 0.50</td>
<td>3.80 ± 0.57</td>
<td>3.60 ± 0.33</td>
<td>4.50 ± 0.36††</td>
</tr>
<tr>
<td>Polar moment of inertia, mm⁴</td>
<td>10,396 ± 1,662</td>
<td>11,062 ± 1,731</td>
<td>12,729 ± 2,075*</td>
<td>3,920 ± 633</td>
<td>5,789 ± 2,179*</td>
<td>7,661 ± 2,397*††</td>
</tr>
<tr>
<td>Strength strain index, mm³</td>
<td>1,947 ± 440</td>
<td>2,179 ± 343</td>
<td>2,074 ± 427</td>
<td>756 ± 102</td>
<td>1,145 ± 548*</td>
<td>1,377 ± 440*</td>
</tr>
</tbody>
</table>

Values are mean ± SD n, no. of subjects. Values in parentheses are adjusted for height and/or weight. pQCT, peripheral quantitative computed tomography; BMD, bone mineral density; BMC, bone mineral content. Significant difference: * vs. control (multiple comparison by Fisher’s PLSD, P < 0.05); † vs. swimmers (multiple comparison by PLSD, P < 0.05).
Results suggest that there is no margin for physical exercise to increase bone mineral, because the cortical bone of young sedentary subjects is already saturated with mineral, and, therefore, bone has expanded in a periosteal direction, resulting in periosteal drift. Contrary to the well-accepted notion from studies using DXA that exercise increases aBMD, the cortical vBMD of jumpers in the present study was lower than that of DXA that exercise increases aBMD, the cortical vBMD of midradius in tennis players (1). Exercise to increase bone mineral, because the cortical vBMD assessed by SSI was significantly greater in female athletes (swimmers and jumpers) than in male athletes. SSI is a function of vBMD and geometry of a bone, and greater vBMD and cortical drift toward periosteal direction result in greater SSI. Interestingly, in the present study, periosteal and endocortical areas were negatively correlated with cortical vBMD in both male and female subjects. Consistently, previous studies observed a negative correlation between relative side-to-side difference in perosteal area and cortical vBMD of midradius in tennis players (1). Exercise was smaller, in both men and women, although the differences were not statistically significant. These observations are consistent with a notion that impact loading (such as jumping) expands periosteal area, whereas active loading (such as swimming) expands endocortical area (10). Jumping and running forces produce ground reaction forces three to five times a person’s body weight, and the force produced at the tissue level can be as high as 10 times the body weight (4, 31).

The greater polar moment of inertia and SSI with cortical drift observed only in female swimmers was unexpected and worth discussing. Parfitt (30) divided the life span into five phases, on the basis of chronological changes of cortical bone geometry (30). The endocortical area expands during puberty, from age 6 to 12 yr, and decreases from adolescence to middle age. Seeman (40) suggested that delayed puberty resulted in larger periosteal and endocortical area in girls but not in boys. As an average in the present study, female swimmers began their training (7.6 ± 1.9 yr) in the earlier part of puberty, but female jumpers began training (12.7 ± 1.5 yr) after puberty, and the athletes had slightly later menarche compared with the controls, although the difference was not statistically significant. Consequently, the different starting age of training between swimmers and jumpers probably caused the cortical drift seen only in female swimmers. The question of whether physical exercise before puberty accelerates the expansion of the endocortical area remains to be settled.

Although the present study is a cross-sectional study, the differences in bone geometry among groups were also observed in the previous studies (1, 15), which assessed side-to-side differences of tennis players’ radius. To adjust potentially confounding differences related to height or weight in the present study, ANCOVA was performed, and the adjusted values were presented, if necessary. However, the statistical differences among group means remained unchanged, even after being size adjusted. The differences in bone geometry and strength indexes in the present study were, therefore, more likely associated with the different types of physical exercise than with the selection bias on the basis of bone size.

Cross-sectional area (cortical area) and polar moment of inertia of cortical bone in jumpers were greater than those in swimmers and controls, suggesting stronger bone against compressive and bending strains. On the other hand, the index for torsional strain assessed by SSI was significantly greater in female athletes (swimmers and jumpers) but not in male athletes. SSI is a function of vBMD and geometry of a bone, and greater vBMD and cortical drift toward periosteal direction result in greater SSI. Interestingly, in the present study, periosteal and endocortical areas were negatively correlated with cortical vBMD in both male and female subjects. Consistently, previous studies observed a negative correlation between relative side-to-side difference in perosteal area and cortical vBMD of midradius in tennis players (1). Exercise
seems to increase the cross-sectional area of bone at the expense of BMD. A preferential increase in cross-sectional area to cortical density has also been reported during the adolescent growth spurt (22). Thus, given a limited calcium intake (22), an increase in cortical drift due to exercise and growth is partly offset by an increase in cortical porosity. Furthermore, it remains to be clarified how bone metabolism between the inner and outer edge of the cortical shell is integrated to affect the changes in cortical vBMD.

In conclusion, 1) an improvement of the mechanical properties of a young athlete’s bone in response to long-term physical exercise is related to geometric adaptation and not to vBMD; 2) increases in periosteal and endocortical area are inversely related to reduced cortical vBMD in athletes; and 3) in female swimmers, physical training started in the earlier part of puberty may contribute to enlarged endocortical area. Thus exercise affects bone geometry through loading mechanical impact on the bone, but it may also affect the endocrine system by delaying puberty.

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