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Paradoxical Adaptation of Mature Radius to Unilateral Use in Tennis Playing

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The positive effects of physical activity on human bone mass have been well documented in many cross-sectional studies comparing athletes with sedentary controls as well as in longitudinal follow-up. By applying peripheral quantitative computed tomography (pQCT), which has the advantage of measuring volumetric bone mineral density (BMD) and the ability to distinguish among trabecular and cortical components, it was demonstrated that cortical BMD of the dominant arm was not greater than that of the nondominant arm. Cortical drift toward the periosteal direction and an increase in cortical thickness resulted in an improvement of mechanical characteristics of the playing arm's midradius. An improvement in the mechanical properties of young adult bone in response to long-term exercise was therefore related to geometric adaptation, but not to an increase in BMD. The manner in which the recruitment and function of bone cells are coordinated differs between the growing and the nongrowing skeleton. In the former, modeling is the dominant mode, and in the latter it is remodeling. In the present study, the side-to-side difference of 92 middle-aged female tennis players who initiated training after bone had matured was analyzed by pQCT. The side-to-side difference detected suggested a paradoxical adaptation of the mature radius to unilateral use during tennis playing, and that tennis playing after bone had matured did not stimulate cortical drift in the periosteal direction, unlike that seen in young subjects. Unexpectedly, the cross-sectional areas (periosteal and endocortical area) of the radius were smaller in the dominant arm than in the nondominant arm in the middle-aged female players. The findings suggest that unilateral use of the arm after the third decade of life suppresses age-related changes in bone geometry. (Bone 30:619–623; 2002) © 2002 by Elsevier Science Inc. All rights reserved.

Key Words: Peripheral quantitative computed tomography (pQCT); Volumetric bone mineral density; Cortical drift; Side-to-side difference.

Introduction

The positive effects of physical activity on human bone mass have been well documented in many cross-sectional studies comparing athletes with sedentary controls[11,13,21] as well as in longitudinal follow-up studies.[5,10,15] In studies of tennis players in which the playing arm was compared with the nondominant arm, the side-to-side differences showed a positive effect of physical loading on bone.[8] Applying peripheral quantitative computed tomography (pQCT), which has the advantage of measuring volumetric bone mineral density (BMD) and distinguishing between trabecular and cortical components, it was demonstrated in young athletes that cortical BMD of the dominant arm was not greater than that of the nondominant arm. Cortical drift toward the periosteal direction and an increase in cortical thickness resulted in an improvement of mechanical characteristics of the playing arm midradius.[1,9] An improvement of mechanical properties of young adult bone in response to long-term exercise was therefore related to geometric adaptation, but not to an increase in BMD.

The ability of bone to adapt to mechanical loading is much greater in the growing than in the nongrowing skeleton and exercise after maturity has a much smaller effect.[22] Furthermore, the manner in which the recruitment and function of bone cells are coordinated differs between the growing and the nongrowing skeleton. In the former, modeling is the dominant mode, and in the latter it is remodeling. In the present study, the side-to-side difference in tennis players who initiated training after bone had matured was analyzed by pQCT and the results revealed a paradoxical adaptation of mature radius to unilateral use in tennis playing.

Materials and Methods

Subjects

Recreational tennis players >35 years of age (n = 134) from local tennis clubs in an urban area were invited to participate in the present study. By direct interview, recreational tennis players, who initiated their playing activity at >30 years of age, had a history of playing over a 3 year period, and did not participate in

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Table 1. Age and training history of players

Range (years)	Number	Age (years)	Starting age (years)	Training period (years)	Menopause (n/group)
35–40	10	38.1 ± 1.9	33.9 ± 1.6	4.2 ± 1.6	0/10
41–50	58	45.1 ± 2.3	35.2 ± 3.0	9.9 ± 3.8[a]	4/58
51–55	24	52.9 ± 1.5	37.6 ± 3.9[a,b]	15.3 ± 3.9[a,b]	16/24
Total	92	46.4 ± 4.8	35.7 ± 2.9	10.7 ± 4.8	20/92

Values for age and training period expressed as mean ± SD.
[a]Significantly different from the 35–40 year age group.
[b]Significantly different from the 41–50 year age group.

other unilateral sports, were selected (n = 102). Players with an incidence of upper extremity fractures (n = 2), ovariectomy (n = 3), or medication affecting bone (n = 5) were excluded from the study. The remaining 92 players, including 5 left-handed players, used only a dominant hand for the forehand stroke, but 66 used both hands for the backhand stroke. The majority of the players (n = 89) initiated their playing while in their thirties. They were playing tennis an average of 3.8 times/week, and the duration of each session was 180 min, ranging from 90 to 360 min. The group characteristics are given in **Table 1**. Written informed consent was obtained before the study.

pQCT

Two sites of radius of both arms were scanned by a pQCT (Densiscan 1000, Scanco Medical, Zurich, Switzerland) with a single-energy X-ray source, according to a method previously described.[1,9,25] The measurement sites of the radius included a proximal site (at midradius, 52 mm from the distal end) and a distal site (at distal radius, 6 mm from the distal end). The distal measuring site, which typically contains 70% trabecular bone, was used specifically for examination of trabecular bone, and a diaphyseal site, which contains >90% cortical bone, was used for cortical bone. All computed tomography scans had a slice thickness of 1.0 mm and a pixel size of 0.36 mm. The high-resolution images were transferred to a Macintosh computer as TIFF images, with fixed scale, density, and resolution (256 × 256 pixels). Periosteal area and endocortical area were measured by the threshold method using NIH IMAGE software (version 1.61, Wayne Rasband, National Institute of Health). Cortical bone area was defined as a region with bone mineral density >0.7 g/cm^3, and cortical thickness was defined as the mean distance between the inner and outer edge of the cortical shell.[29] Coefficients of variation for the triplicate measurements on three human subjects after repositioning were 0.10%–0.72% for volumetric BMD, 0.44%–0.74% for bone area, and 0.79% for cortical thickness. Polar moment of inertia, section modulus, and strength strain index (SSI) were calculated as measures of bone strength.[26]

Statistical Analysis

Statistical analysis was performed using the STATVIEW program and data are expressed as means ± SD. The side-to-side difference in parameters was analyzed by paired *t*-test. Statistical significance was taken at the $p < 0.05$ level.

Results

Side-to-side differences in geometric parameters, BMD, bone mineral content (BMC) and indexes of bone strength of radius were analyzed with a paired *t*-test as shown in **Table 2**. Endocortical area, periosteal area, BMC, and indexes of mechanical strength (moment of inertia, section modulus, and SSI) of dominant midradius were significantly smaller compared with those of the nondominant radius. There was no significant side-to-side difference in cortical thickness, cortical BMD, and BMD of whole bone at the midradius. At the distal portion of the radius,

Table 2. Peripheral quantitative computed tomography (pQCT) parameters of the radius

	Nondominant	Dominant	Increase (%)	*Z* score
Midradius				
Endocortical area (cm^2)	0.300 ± 0.106	0.278 ± 0.094[a]	−7.3	−0.21
Periosteal area (cm^2)	1.061 ± 0.15	1.007 ± 0.14[a]	−5.1	−0.36
Cortical thickness (cm)	0.275 ± 0.027	0.272 ± 0.028	−1.1	−0.11
Cortical BMD (g/cm^3)	1.946 ± 0.082	1.942 ± 0.087	−0.2	−0.05
Whole BMD (g/cm^3)	1.404 ± 0.166	1.415 ± 0.164	+8.0	+0.07
BMC (g/mm)	0.147 ± 0.017	0.141 ± 0.017[a]	−4.1	−0.36
Moment of inertia (mm^4)	1744 ± 460	1598 ± 413[a]	−8.4	−0.32
Section modulus (mm^3)	233 ± 44	219 ± 41[a]	−6.0	−0.32
SSI (mm^3)	376 ± 71	352 ± 66[a]	−6.4	−0.34
Distal radius				
Periosteal area (cm^2)	4.16 ± 0.60	3.77 ± 0.56[a]	−9.4	−0.65
Trabecular BMD (g/cm^3)	0.363 ± 0.070	0.383 ± 0.060[b]	+5.5	+0.29
Whole BMD (g/cm^3)	0.656 ± 0.120	0.756 ± 0.115[a]	+15.2	+0.83
BMC (g/mm)	0.273 ± 0.065	0.286 ± 0.065	+4.9	+0.21

Values expressed as mean ± SD.
KEY: BMC, bone mineral content; BMD, bone mineral density; SSI, strength strain index.
Side-to-side difference: [a]$p < 0.01$, [b]$p < 0.05$.

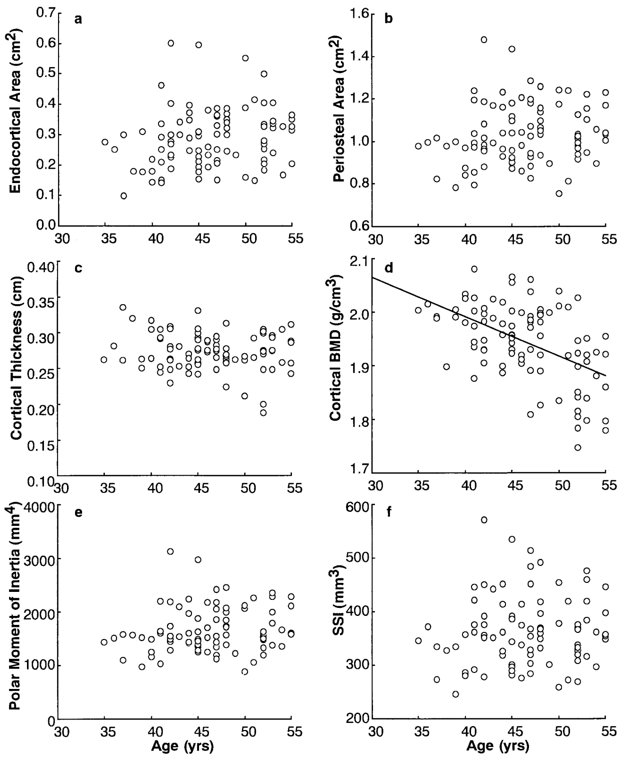

Figure 1. Endocortical area (a), periosteal area (b), cortical thickness (c), cortical BMD (d), polar moment of inertia (e), and strength strain index (f). Means of the dominant and nondominant arm of each subjects were plotted against age. Cortical BMD was significantly related to age ($p < 0.01$).

the periosteal area of the dominant radius was significantly smaller and BMD of the trabecular and whole bone were significantly greater in comparison to those of the nondominant radius. BMC of dominant distal radius was greater than that of nondominant radius, but the difference was not statistically significant ($p = 0.052$).

Because the present study recruited subjects in the age range of 35–55 years, dependency of the geometric parameter, BMD, and indexes of mechanical strength on age were assessed, as shown in **Figure 1** and **Table 3**. BMDs of cortical bone and whole bone at the midradius were lower in older subjects, and age-related differences were significant when statistical analyses were applied on the dominant, nondominant, and mean of both radii ($p < 0.01$). The age-related difference in endocortical area and cortical thickness of the midradius was statistically significant in the nondominant radius, but the relation was not statistically significant in the dominant radius and the mean of both radii. The periosteal area of the midradius of the nondominant radius showed a tendency to increase with age, but the difference was not statistically significant (nondominant radius, $p = 0.089$; dominant radius, $p = 0.140$).

Dependency of side-to-side differences in bone parameters on age and training duration were also assessed (Table 3). The side-to-side difference in endocortical area was negatively correlated with age and that in cortical thickness was positively correlated with training period (**Figure 2**). Side-to-side differences in other parameters were not correlated with age or training period.

Discussion

In addition to age-related changes, there was large individual variability in geometric parameters, BMD, BMC, and mechanical strength, as shown in Figure 1. Recent studies have suggested a strong genetic influence on BMD,[3,6,7,17,19,20,23] and it is reasonable to assume that geometric parameters such as endocortical area and periosteal area are also influenced by genetic factors. In addition, the nutritional and hormonal influence on bone metabolism and exercise habit other than tennis must also be considered as sources of individual variability in bone geometry and BMD. To eliminate the influence of these genetic and environmental influences, we analyzed the side-to-side difference of the radius of tennis players.

Compared with the nondominant arm, the endocortical and periosteal areas of the dominant arm were smaller and long-term unilateral use by tennis playing did not stimulate cortical drift toward the periosteal direction in our subjects. Side-to-side differences in geometric parameters, index of mechanical strength, BMD, and BMC of the tennis players remained statistically significant when 20 menopausal players were excluded from the statistical analysis. These findings were unexpected and quite in contrast to previous observations on young tennis players,[1,9] where cortical drift toward the periosteal direction was observed in the dominant arm. A comparison of the present observations on middle-aged recreational tennis players, and a previous one on young athletic players, suggests several possibilities. The first possible explanation is that unilateral mechanical loading stimulated cortical drift only during the adolescent period, but not after the third decade of life. Bone loss from the endocortical surface is enhanced and it outpaces bone formation in the periosteal area and thus cortical thickness tends to decrease throughout most of life except for a relatively short period during adolescence.[24] It is therefore conceivable that habitual exercise, after peak bone mass has been attained, suppresses acceleration of bone loss from the endocortical area, resulting in suppression of compensatory bone formation at the periosteal surface. Interestingly, we showed that age-related expansion of the endocortical area was statistically significant in the nondominant radius, but not in the dominant. Second, differences in intensity of exercise between athletic and recreational players resulted in a different effect on bone geometry. Third, subject gender may have interacted with the effect of exercise on bone metabolism. Previous reports on radial BMC of male life-time tennis players (73 ± 12 years) are noteworthy.[12] BMC measured by transmission scanning with a low-energy X-ray beam at the midradius of the dominant arm was greater than that of the nondominant arm. Although a residual effect of training history during the adolescent period cannot be excluded in the study of life-time tennis players, it is possible that hard training done by male tennis players enhanced the BMC of cortical bone, whereas the female recreational players investigated in the present study did not.

After the third decade of life, the endocortical area begins to increase and expansion of the periosteal area slows, resulting in decreased cortical thickness.[22] Consistent with previous observations in femoral radiographs, direct measurement of specimens, and mathematical model-based bone modeling theory,[2,16,22,27,30] progressive increases in endocortical and periosteal areas and decreases in cortical thickness were observed in the midradius of the nondominant arm, although dependency of periosteal area on age was not statistically significant ($p = 0.089$) due to large individual variability. It is noteworthy that age-related differences in these parameters were not observed in the dominant radius, suggesting that unilateral use of the arm after the third decade of life suppressed age-related changes in bone geometry.

Table 3. Correlation coefficient of peripheral quantitative computed tomography (pQCT) parameters and age or training period

	Age				Training,
	Mean[a]	Dominant[b]	Nondominant[c]	Side-to-side[d]	Side-to-side[e]
Midradius					
Endocortical area	0.193	0.151	0.229[f]	−0.208[f]	−0.159
Periosteal area	0.172	0.155	0.178	−0.069	0.001
Cortical thickness	−0.153	−0.080	−0.215[f]	0.203	0.208[f]
Cortical BMD	−0.508[g]	−0.467[g]	−0.404[g]	−0.085	−0.120
Whole BMD	−0.325[g]	−0.289[g]	−0.333[g]	0.079	0.040
BMC	−0.099	−0.078	−0.106	0.042	0.068
Moment of inertia	0.125	0.134	0.108	0.024	0.046
Section modulus	0.152	0.165	0.128	0.050	0.127
SSI	0.076	0.087	0.059	0.036	0.086
Distal radius					
Periosteal area	0.083	0.035	0.116	−0.117	−0.050
Trabecular BMD	−0.044	−0.100	−0.116	0.028	0.139
Whole BMD	−0.134	−0.026	−0.051	0.033	0.033
BMC	0.021	0.008	0.029	−0.020	0.001

KEY: BMC, bone mineral content; BMD, bone mineral density; SSI, strength strain index.
[a]Age vs. mean of both arms.
[b]Age vs. dominant radius
[c]Age vs. nondominant radius.
[d]Age vs. side-to-side difference.
[e]Training period vs. side-to-side difference.
[f]$p < 0.05$; [g]$p < 0.01$.

Similar to midradius, periosteal area increased and BMD decreased with age in the distal radius, but the age-related changes were not statistically significant in both arms. At the distal radius, which typically contains 70% trabecular bone, the BMD of the dominant arm was greater than that of nondominant arm, consistent with a previous report showing that BMD of trabecular bone was more sensitive to the effects of exercise than cortical bone.[28] Periosteal area at the distal site of the dominant arm was smaller than that of the nondominant arm and this observation in middle-aged tennis players is quite in contrast to that in young tennis players. As noted earlier, the differences in the findings between young athletic tennis players and middle-aged recreational tennis players remains to be clarified.

To evaluate the physiological significance of suppressed cortical drift, indexes of mechanical strength were calculated. SSI, which is a function of geometry and BMD, slightly and significantly decreased in the dominant radius in comparison to the nondominant radius. Thus, BMC and bone strength decreased at the midportion of the dominant radius. On the other hand, BMC increased at the distal portion of the dominant radius, although the difference did not reach statistical significance. One possible explanation for these observations is that tennis playing triggered a bone mass shift from the middle to the distal portion within the radius. The possibility of bone mass shift within a body by physical exercise has already been indicated in studies wherein the nondominant arm of the tennis players was "the weakest of all" among dominant and nondominant arms of players and sedentary controls,[9] and BMD of the skull decreased in athletes whose femoral BMD had increased.[4,14] In an experiment on rats, controlled dynamic loading produced a change in shape, which stimulated periosteal expansion in some areas and decreased it in others.[18] The study emphasized assessment of whole bone architecture instead of measurement at select bony sites, an approach that remains to be done in a human study.

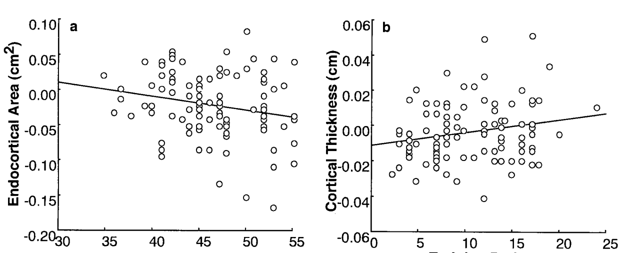

Figure 2. Dependency of side-to-side difference in endocortical area on age (a) and cortical thickness on training period (b). Side-to-side differences for each individual are plotted against age or training period.

Although statistically significant, side-to-side difference in geometric parameters, BMD, BMC, and indexes of mechanical strength were relatively small. These results clearly suggest that the most of the individual variability in parameters of the radius derived from factors other than age and unilateral use of the arm. The present study therefore focused on side-to-side differences in players' radius, and "control" subjects were not recruited. Although a side-to-side difference in radius was not detected in the control group in our previous study on young subjects,[1] it remains possible that the side-to-side difference in middle-aged subjects in the present study reflects not only tennis playing but lifelong daily unilateral use. This possibility remains to be clarified.

Unlike what was seen in young subjects, tennis playing after bone had matured did not stimulate cortical drift toward the periosteal direction in middle-aged female subjects. Unexpectedly, the periosteal area at the middle and distal radius and endocortical area at the midradius were smaller in the dominant arm than in the nondominant arm of the middle-aged players. These findings suggest that unilateral use of the arm after the third decade of life suppresses age-related changes in bone geometry, although the mechanism behind this phenomenon remains to be clarified.

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