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Bone geometry in response to long-term tennis playing and its relationship with muscle volume: A quantitative magnetic resonance imaging study in tennis players

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Abstract

The benefit of impact-loading activity for bone strength depends on whether the additional bone mineral content (BMC) accrued at loaded sites is due to an increased bone size, volumetric bone mineral density (vBMD) or both. Using magnetic resonance imaging (MRI) and dual energy X-ray absorptiometry (DXA), the aim of this study was to characterize the geometric changes of the dominant radius in response to long-term tennis playing and to assess the influence of muscle forces on bone tissue by investigating the muscle–bone relationship. Twenty tennis players (10 men and 10 women, mean age: 23.1 ± 4.7 years, with 14.3 ± 3.4 years of playing) were recruited. The total bone volume, cortical volume, sub-cortical volume and muscle volume were measured at both distal radii by MRI. BMC was assessed by DXA and was divided by the total bone volume to derive vBMD. Grip strength was evaluated with a dynamometer. Significant side-to-side differences ($P < 0.0001$) were found in muscle volume (+9.7%), grip strength (+13.3%), BMC (+13.5%), total bone volume (+10.3%) and sub-cortical volume (+20.6%), but not in cortical volume (+2.6%, ns). The asymmetry in total bone volume explained 75% of the variance in BMC asymmetry ($P < 0.0001$). vBMD was slightly higher on the dominant side (+3.3%, $P < 0.05$). Grip strength and muscle volume correlated with all bone variables (except vBMD) on both sides ($r = 0.48$–0.86, $P < 0.05$–0.0001) but the asymmetries in muscle parameters did not correlate with those in bone parameters. After adjustment for muscle volume or grip strength, BMC was still greater on the dominant side. This study showed that the greater BMC induced by long-term tennis playing at the dominant radius was associated to a marked increase in bone size and a slight improvement in volumetric BMD, thereby improving bone strength. In addition to the muscle contractions, other mechanical stimuli seemed to exert a direct effect on bone tissue, contributing to the specific bone response to tennis playing.

Keywords: Bone geometry; Magnetic resonance imaging; Volumetric bone mineral density; Unilateral loading; Absorptiometry

Introduction

Impact-loading activity is now considered as an effective strategy to improve bone health. The skeletal sites which are submitted to mechanical stimuli display greater values of bone mineral content than the unloaded sites, as demonstrated by dual energy X-ray absorptiometry (DXA) data [1,2]. Recently, it has been shown that weight bearing activities were associated with higher bone mineral density when they induced high impacts (volleyball, hurdling) rather than low impacts (orienteering, cross-country skiing) [3]. This observation has been reinforced by the comparison of the dominant and nondominant upper limbs in tennis or

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squash players [4–11]. Tennis strokes provoke repetitive mechanical strains in the dominant forearm, due to racket vibrations [12], torsional forces [13] and muscle contractions [14]. Additionally, studying unilateral activities enables an elimination of the confounding effects of genetic, hormonal and nutritional factors.

Bone mineral accrual affects bone mechanical strength. The magnitude of the change in bone strength depends partly on whether the "extra" bone mineral content is associated with an increase in bone size, volumetric bone mineral density (vBMD) or both. The gain in bone resistance to compressive, bending or torsional loads is indeed more pronounced when the new added mineral mass is placed further from the neutral axis of the bone, inducing an increase in bone size [15–18].

In the past 10 years, most of the human studies dealing with bone and exercise were based on DXA data. Nevertheless, estimating bone volume requires three-dimensional techniques. The use of peripheral quantitative computed tomography (pQCT) made a breakthrough in the understanding of the bone response to mechanical loading. By its capacity to measure both bone mineral content and three-dimensional bone geometry at appendicular sites, this device gave the opportunity to assess vBMD. Mechanical loading has been shown to exert a limited effect on cortical vBMD in long bone diaphyses, the effect being slightly negative [19,20] or not significant [20–22] whereas loading induced a clear positive effect on trabecular vBMD in long bone epiphyses [19,22,23]. The greatest changes in gross geometry were found in long bone diaphyses, where a marked increase in total bone cross-sectional area was observed [19,20,23].

Muscle forces have been proposed to be the largest voluntary loads to which bone has to adapt in order to keep its mechanical environment stable [24]. Understanding the muscle–bone relationship could certainly help to better describe the mechanisms by which bone responds to mechanical stimuli during physical activity.

With regard to this objective, magnetic resonance imaging (MRI) is a promising nonionizing 3D-technique. It has already been used to study the effects of growth [25,26] or mechanical loading on bone geometry [27–29], as being a valid and reproducible method [30,31]. The major advantage of MRI technology lies in its capacity to measure the cross-sectional area of both muscle and bone on multiple contiguous slices, and thus to study the muscle–bone interaction [29,32]. DXA is considered as the gold standard method to determine bone mineral content. Combining the two techniques enables an estimate of vBMD, provided that DXA-derived bone mineral content and MRI-derived total bone volume are carefully measured on the same region of interest [33].

The objectives of this study were (1) to characterize the bone response to loading in terms of bone geometry and volumetric bone mineral density in young adults who started playing tennis prior to puberty, and (2) to assess the role of muscle forces in the bone response by investigating the muscle–bone relationship.

Materials and methods

Subjects

Twenty regional-level tennis players (10 men and 10 women, all Caucasian) were recruited in the neighborhood of Orléans (France). Subjects comprised a sub-sample of volunteers from a larger study [34], who accepted to take part in a thorough analysis including MRI scanning. All were right-handed. They had been practicing tennis for 10 to 20 years, except one player who had experienced 7.4 years of practice. The subjects were still playing tennis at the time of the experiments and they took part in regular competition.

Non-inclusion criteria were any past fracture at the radius or ulna as well as any medical disorder or treatment known to affect bone metabolism (exception made for oral contraceptives in 6 out of 10 women). None of the female subjects reported having experienced amenorrhea during their teenage years or twenties. Informed written consent was obtained from each participant. The study was approved by the Ethics Committee of the Region of Tours, France.

Training history

The training history was assessed by questionnaire. The participants recorded their starting age of regular tennis playing (at least 1 h per week), number of years of practice and training volume (hours per week) for each year. Adding up the whole training volume for each subject yielded the total amount of practice for the entire career (total training time), after taking into account the breaks due to injuries or holidays.

Anthropometric measurements

Body weight (in kg) was measured on a balance-beam scale (SECA 709, Hamburg, Germany), the subjects wearing only underwear. Body height (in cm) was measured in the upright position to the nearest 1 mm with a standard laboratory stadiometer (SECA, Hamburg, Germany). Dominant and nondominant forearm lengths were determined between the ulnar styloid process and the olecranon using a plastic tape. Dominance was established according to the arm used in serving.

Magnetic resonance imaging (MRI)

Image acquisition

Bone and muscle geometric parameters were measured on both radii by MRI with a whole-body system operating at 1.5 T (Siemens Magnetom Vision, Erlangen, Germany) by using a commercial high resolution wrist coil. Subjects

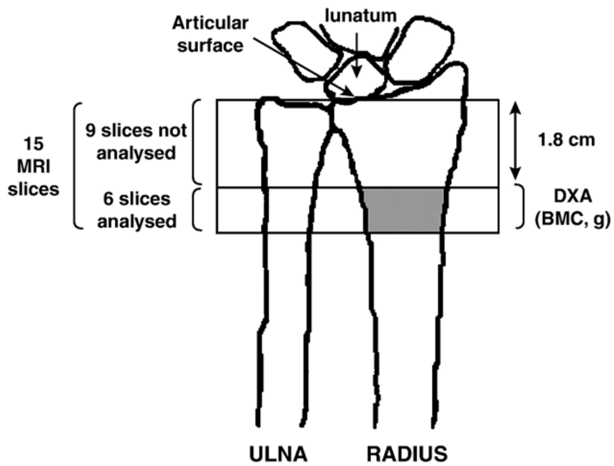

Fig. 1. Location of the region of interest (shaded area) at the distal radius on MR and DXA images. The regions were carefully matched for both methods, taking the radial articular surface as the reference landmark.

laid prone, with the arm to be imaged extended overhead. They were asked to remain motionless during the acquisition. T1-weighted spin-echo images at a repetition time of 645 ms and echo time of 20 ms were acquired in the axial plane. Two acquisitions were made. Field of view was 100 mm^2 and matrix size 512 × 512, which gave an in-plane resolution of 0.195 × 0.195 mm. Two-millimeter axial slices were scanned along the length of the radius. A total of 15 contiguous slices were obtained, proximally from the articular surface between the distal radius and the lunatum (Fig. 1). This articular surface was chosen as an anatomic landmark for two reasons: (1) it appears clearly on the MR images and (2) the surface is perpendicular to the long axis of the radius, enabling to align the most distal slice right on this surface. In addition, this landmark has already been chosen in a previous study [35].

Only the six most proximal slices were kept for further macroarchitectural analysis, covering 1.2 cm of the distal forearm. The cortical rim, which appears in black on the MR images, could be clearly identified on those proximal slices. At the ultra-distal radius, the cortical rim is much thinner, making the distinction of the periosteal and endocortical surfaces very difficult. As a consequence, the 9 most distal slices were eliminated. Macroarchitectural analysis was located proximally to the distal end of the radius, at a distance corresponding approximately to 10% of the radial length. This site is considered to give a good estimate of the cross-sectional properties of the radius at its distal end [36].

Measurement of bone geometry

Images in DICOM format were converted in bitmap format using OSIRIS software (Digital Imaging Unit, Centre of Medical Informatics, University Hospital of Geneva, version 4.19). They were then analyzed using the Mazda imaging analysis software (Institute of Electronics, Technical University of Lodz, Poland, version 3.20). Total bone cross-sectional area and sub-cortical area were manually determined on enlarged views of the six slices (Fig. 2). Total area was defined as the area contained within the periosteal border. Sub-cortical area was defined as the area contained within the endocortical surface. Cortical area was total area minus sub-cortical area. Anatomical muscle area was manually defined by tracing discontinuous regions of interest encompassing all muscle groups at the distal forearm. The tendons were included in the region of interest (appearing in black on Fig. 2). The muscle area comprised all the muscles (and tendinous insertions) that were present at the distal radius (pronator quadratus, brachioradialis, in addition to the flexors and extensors of the carpus and fingers). Volumetric measurements were calculated as the summed products of measured areas and slice thickness over the 6 slices. The outcome parameters were the total bone volume, the cortical

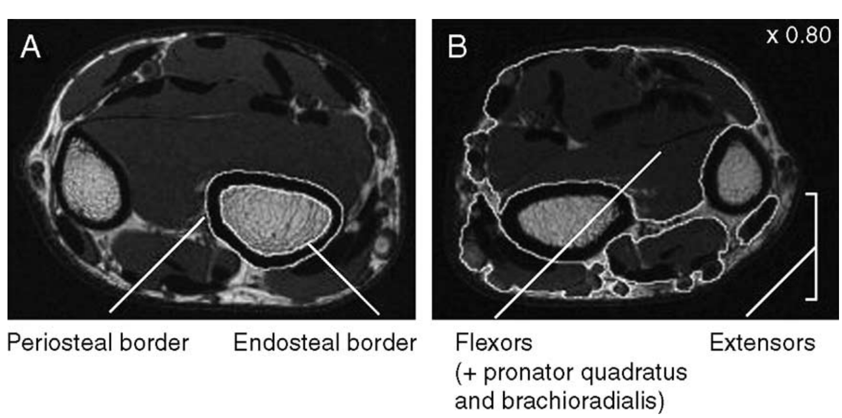

Fig. 2. An example of MRI scans at the dominant (A) and nondominant (B) forearms of a 24-year-old male player (17.6 years of practice, starting age of playing: 5.5 years). The two slices were obtained at the same level of the forearm. On scan A, the trace outlines the periosteal (outer) and endosteal (inner) borders, enabling to delimit the total bone area and sub-cortical area, respectively. On scan B, the muscle groups were delineated in order to estimate the cross-sectional muscle area. In this player, the relative side-to-side differences amounted to 24.5% for CMO, 28% for total bone volume, 52% for sub-cortical volume, 7.5% for cortical volume and 14.5% for muscle volume (magnification: ×0.80).

volume, the sub-cortical volume and the muscle volume, all expressed in mm^3.

The reproducibility of the MRI acquisition was assessed in three volunteers with repositioning between measurements. The root-mean-square coefficients of variation [37] were 1.9% for total bone volume, 0.5% for sub-cortical volume, 3.2% for cortical volume and 1.5% for muscle volume. To assess intraoperator short-term precision for MRI scan analysis, seven randomly selected scans were analyzed twice. Root-mean-square coefficient of variation for analysis ranged from 0.8% to 5.2%.

Dual energy X-ray absorptiometry (DXA)

Bone mineral content (BMC, in g) at the distal radius was determined by DXA (Delphi QDR® Series, Hologic Inc., Waltham, MA, USA). A region of interest (ROI) was derived from the distal radius scan, thereby matching the region of interest scanned with MRI (Fig. 1). Precision error for the DXA measures at the distal radius, as evaluated by the root-mean-square coefficient of variation, was less than 1.1% [34]. The ROI was placed 1.8 cm far from the articular surface of the distal radius. This distance corresponded to the 9 MRI slices that were not analyzed. The ROI was 1.2-cm long, matching the 6 MRI slices analyzed for geometry. The positioning of the region of interest was tested for reproducibility, based on two repeated analyses of seven data sets. The root-mean-square coefficient of variation was 0.37% for BMC.

Estimation of the volumetric bone mineral density

Total volumetric bone mineral density (vBMD) was estimated by combining DXA and MRI, as previously proposed [33]. vBMD (in $mg \cdot cm^{-3}$) was calculated as the ratio of DXA-derived BMC on the MRI-derived total bone volume.

Grip strength measurement

Grip strength (in N) was measured by means of a hand-held dynamometer equipped with a strain gauge (Scaime ZF 200 kg—no. 30141). The device was calibrated monthly with known weights over a force range from 0 to 850 N. The short-term precision of the device (root-mean-square coefficient of variation) was 0.56%. Measurements were taken with the subject seated on a chair. The upper extremity was positioned in neutral adduction and flexion, with the elbow flexed at 90° and the forearm in a mid-prone position. The wrist was maintained in a neutral position by the device. One warm-up trial was made with each hand in order to adjust the grip to the size of the hand. Three maximal efforts were performed alternatively with right and left hand, beginning with the right one. Each trial was followed by a 30-s resting period to minimize fatigue. The best value was recorded as grip strength.

The in-vivo coefficient of variation of the grip strength measurement was 4.7% for the dominant side and 3.7% for the nondominant side.

Statistical analysis

All the data are shown as mean ± standard deviation. The gaussian distribution of the parameters was tested by the Kolmogorov–Smirnov test. The comparison of the parameters measured at the dominant and nondominant forearms was performed using a parametric paired t test. One-way ANOVA for paired samples was used to compare the side-to-side differences in muscle and bone parameters between men and women, and between one-handed and two-handed backhand players. In case of an interaction between the "dominance effect" and the "gender effect", we used a one-way ANOVA to compare the magnitude of the asymmetry between genders. Relative side-to-side differences in muscle and bone parameters were expressed as the percentage of the nondominant value ($\Delta\% = (\text{dominant} - \text{nondominant}) / \text{nondominant} \times 100$). Absolute side-to-side differences were the dominant value minus the nondominant value. Relationships between the significant variables were tested by the Pearson product moment correlation coefficient.

Results

General descriptive characteristics of the subjects

The characteristics of the subjects are given in Table 1. The male subjects were significantly older, taller and heavier than their female counterparts ($P < 0.05$). No difference was found between men and women with regard to tennis playing history although a tendency was observed towards a longer tennis practice in male players.

Table 1
Characteristics of the tennis players included in the study of forearm bone geometry

	Women (n = 10)	Men (n = 10)	Combined (n = 20)
Age (yr)	20.7 ± 1.9	25.6 ± 5.5*	23.1 ± 4.7
Height (cm)	167.8 ± 4.1	177.7 ± 5.3***	172.8 ± 6.9
Weight (kg)	60.3 ± 3.2	72.2 ± 6.4***	66.2 ± 7.9
Backhand technique: one-handed/two-handed	1/9	8/2	9/11
Starting age of playing (yr)	7.8 ± 2.2	9.1 ± 3.6	8.4 ± 3.0
Years of playing	12.9 ± 2.7	15.8 ± 3.6	14.3 ± 3.4
Estimated total training time (h)	2011 ± 787	2837 ± 1664	2424 ± 1336
Currently training hours (h/week)	4.5 ± 1.5	4.5 ± 1.6	4.5 ± 1.6

Values are means ± SD. Difference between males and females: *$P < 0.05$; ***$P < 0.001$.

Asymmetry between the dominant and nondominant forearm

In the whole sample, muscle volume, grip strength, BMC, total bone volume and sub-cortical volume were greater at the dominant radius than at its nondominant counterpart ($P < 0.0001$). The relative asymmetry amounted to 9.7% for muscle volume, 13.3% for grip strength, 13.5% for BMC, 10.3% for total bone volume and 20.6% for sub-cortical volume. The side-to-side difference for cortical volume did not reach statistical significance (+2.6%, ns). In addition, vBMD was slightly higher on the dominant side (637.7 ± 86.1 versus 616.9 ± 75.3 mg·cm^{-3}, $P < 0.05$), with an asymmetry reaching 3.3%. The dominant forearm was longer than the nondominant one (+1.3%, $P < 0.05$). However, the side-to-side differences in bone and muscle parameters were still significant after adjustment for forearm length.

Table 2 shows the data of forearm length, muscle volume, grip strength and bone parameters on both sides in men and women, as well as the relative side-to-side differences. Men showed greater forearm length than women on the dominant and nondominant sides. Even so, the asymmetry in this parameter, either relative or absolute, did not differ between groups. One-way ANOVA for paired samples revealed that there was an interaction between the "dominance effect" and the "gender effect" for muscle volume, total bone volume, sub-cortical volume and BMC, even after adjustment for age, body weight, body height or number of playing years. The interaction disappeared after adjustment for forearm length, except for BMC. Further analysis showed that male players displayed a greater absolute asymmetry than the female players for muscle volume, sub-cortical volume and BMC ($P < 0.05$). After adjusting for the asymmetry in forearm length, only the difference in BMC asymmetry persisted between genders.

The one-handed backhand players showed a greater absolute side-to-side difference in cortical volume (+67.5 ± 56.8 mm^3, $P < 0.05$) than the two-handed backhand players (+6.8 ± 64.2 mm^3, ns). The absolute side-to-side difference in BMC was also higher in the one-handed backhand players.

The training history parameters (number of playing years, starting age of playing) correlated neither with the side-to-side differences in bone parameters nor with the asymmetries in muscle volume or grip strength.

Relationships between muscle and bone parameters

Grip strength was closely linked to muscle volume ($r = 0.84$ and 0.89 on the dominant and nondominant sides, respectively, $P < 0.0001$). Grip strength also correlated to all bone parameters, except vBMD, the strongest correlations being observed with cortical volume ($r = 0.84$ and 0.86, $P < 0.0001$) and BMC (0.82 on both sides, $P < 0.0001$). The correlations remained significant after adjustment for body weight, body height or forearm length.

Significant correlations were observed between muscle volume and bone parameters (except vBMD) on both sides, the r values ranging from 0.48 to 0.83 (P ranging from <0.05 to <0.0001). The side-to-side difference in grip strength was not associated with any of the bone asymmetries. Neither was the side-to-side difference in muscle volume.

DXA-obtained BMC was highly correlated with MRI-obtained bone geometric parameters, the highest r values being observed with cortical volume (r = 0.95–0.98, $P < 0.0001$, on the dominant and nondominant sides, respectively). The r values were lower with total bone volume (0.83–0.83, $P < 0.0001$) and sub-cortical volume (0.65–0.63, $P < 0.01$). Additionally, the relative asymmetry in BMC did correlate with the relative asymmetry in geometric parameters. The r values reached 0.65 for cortical volume ($P < 0.01$), 0.86 for total bone volume ($P < 0.0001$) and 0.84 for sub-cortical volume ($P < 0.0001$). All the aforementioned correlations remained significant after adjustment for body weight, body height and forearm length, except the correlations between BMC and the sub-cortical volume on both sides. Relative side-to-side difference in total bone volume explains 75% of the variance of the relative side-to-side difference in BMC ($P < 0.0001$).

Table 2

Forearm length, muscle volume, grip strength, total bone volume, cortical volume, sub-cortical volume, bone mineral content (BMC) and derived volumetric bone mineral density (vBMD) on the dominant and nondominant sides in female and male tennis players. Relative side-to-side differences are given as the percentage of the nondominant value (Δ%)

	Female players (n = 10)			Male players (n = 10)		
	Dominant	Nondominant	Δ%[a]	Dominant	Nondominant	Δ%[a]
Forearm length (cm)	24.4 ± 0.8	24.2 ± 0.8	0.7	26.3 ± 0.7	25.8 ± 0.6**	1.9
Muscle volume (mm^3)	13,196.6 ± 2364.9	12,097.4 ± 2068.4†	9.0	19,031.7 ± 1686.3	17,264.2 ± 1611.5†	10.4
Grip strength (N)	477.3 ± 110.5	424.0 ± 91.2***	12.5	701.2 ± 103.0	613.8 ± 64.1**	14.1
Total bone volume (mm^3)	2010.5 ± 327.4	1897.8 ± 330.7*	6.4	2862.0 ± 507.3	2504.0 ± 323.4**	14.2
Cortical volume (mm^3)	1113.0 ± 97.8	1095.6 ± 107.0	1.8	1483.6 ± 148.6	1432.8 ± 117.5	3.5
Sub-cortical volume (mm^3)	897.4 ± 260.8	802.3 ± 247.7*	13.3	1378.5 ± 440.3	1071.2 ± 255.7**	27.9
BMC (g)	1.28 ± 0.12	1.16 ± 0.12†	10.3	1.77 ± 0.18	1.52 ± 0.15†	16.7
vBMD (mg·cm^{-3})	644.2 ± 75.9	620.3 ± 73.6*	3.9	631.3 ± 99.0	613.4 ± 80.8	2.7

Dominant > Nondominant: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; $^†P < 0.0001$.

[a] Δ% = (Dominant − Nondominant) / Nondominant × 100.

Muscle–bone relationship in the dominant and nondominant forearms

One-way ANOVA revealed that BMC adjusted for muscle volume was greater on the dominant side than on the nondominant side. Adjustment for grip strength gave the same result. Total bone volume, cortical volume and sub-cortical volume, when adjusted for muscle volume or grip strength, did not differ significantly between both radii.

Discussion

This study showed that long-term tennis players displayed a greater bone mass at the dominant distal radius, which was associated to a marked increase in bone size and a slight improvement in volumetric BMD.

The increase we found in BMC at the dominant distal radius was consistent with previous findings obtained by pQCT at the same site, values ranging from +12% to +14.7% [19,20,23]. In the present study, the asymmetry in total bone volume explains 75% of the variance in BMC asymmetry, demonstrating that the tennis-induced bone response was specifically achieved through bone enlargement. The asymmetry in total bone volume (10.3%) was close to that found in total bone cross-sectional area by Ashizawa et al. (+6.8%) [19] and Kontulainen et al. (+11%) [23]. A much larger asymmetry in total bone area (+19.4%) has already been reported but the former top-level players included in this study displayed a tennis history as long as 20 years [20]. In addition, the authors recruited male players. Gender has been suspected to modulate the bone response to loading [38] since the increase in BMD was detected earlier in men than in women [2]. In our study, men showed a greater asymmetry in BMC and sub-cortical volume than female players. The difference remained significant for BMC after adjustment for the asymmetry in forearm length. However, only one woman in 10 played the backhand with the dominant hand (versus 8 males in ten, Table 1), a technique that increases the loads applied on the dominant limb [39]. As a result, the higher asymmetries found in men could be due to their preferential backhand technique or to a gender effect.

The fact that forearm length differed between the dominant and nondominant limbs and between genders raised the question of the positioning of the region of interest. The most distal slice was located at an absolute distance of 1.8 cm from the distal end of the radius. As a result, the relative positioning of the region of interest differed between sides and genders, implying that the geometry and relative content in cortical and trabecular bone may vary as well [40]. Since the mean difference in forearm length between sides was less than 0.5 cm (Table 2), the comparison between sides must not have been affected. On the contrary, this methodological issue represented a significant limitation in comparing men and women because forearm length was nearly 2 cm longer in men. In addition, one must bear in mind that the evaluation of bone geometry and vBMD by MRI and DXA has not been validated at the distal radius.

In previous racket sports studies, consistent findings have demonstrated that physical loading exerts a positive effect on cortical bone area, the asymmetry between both limbs ranging from 7 to 31.9% (Table 3). Such results were confirmed by cross-sectional studies [21,22,41]. At some skeletal sites, cortical bone volume could even increase at the expense of cortical bone density, as several authors reported a slight decrease in cortical vBMD [19,20].

The asymmetry in cortical volume observed in our study was weak (+2.6%, ns) comparatively to that in sub-cortical volume (+20.6%). The gain in bone size was mainly achieved through an enlargement in the marrow cavity. Since the subjects recruited for this study were skilled players, they frequently applied spins to the tennis ball. The torsional forces encountered by the wrist—and consequently by the distal radius which is very close to the wrist—are larger during this type of strokes than during flat strokes. Torsional loading preferentially favors an increase in bone size, associated to an enlarged marrow cavity but not necessarily to a greater cortical thickness [42]. As a consequence, if the distal radius was principally submitted to bending loads, it could explain why the asymmetry we observed in cortical volume was not significant.

During childhood and adolescence, changes in medullary volume depend on two mechanisms occurring at the endocortical surface: (1) the endocortical resorption due to bone growth, enlarging the marrow cavity and (2) the endocortical apposition of bone mineral due to physical loading, contracting the marrow cavity. The respective behavior of the periosteal and endocortical surfaces in response to loading determines bone geometry [43,44]. It has been shown that this behavior is not only site-specific [45] but also maturation-specific [46]. Periosteal apposition accounts for most of the bone response to loading before puberty, endocortical contraction contributing later in puberty [27]. Furthermore, a negative correlation has been found between the starting age of playing and the asymmetry in medullary area [29]. The relatively young starting age of playing observed in our sample (8.4 years) could partly explain the large increase in sub-cortical volume we observed at the dominant radius. The lack of consistency in the results concerning the asymmetry in sub-cortical area (Table 3) could also stem from the various skeletal sites which were analyzed and the large interindividual variability in this parameter [20].

The structural changes in total bone volume of the dominant radius, which are supposed to have occurred during the first few years of practice, were perhaps sufficient to reduce the strains in the bone. Therefore, the cortical volume did not increase significantly, the mechanical environment of the dominant radius being almost stabilized

Table 3
Side-to-side differences (Δ%[a]) in sub-cortical area (SCA) and cortical area (CA) reported in previous racket sports studies using peripheral quantitative tomography (pQCT) or magnetic resonance imaging (MRI)

	Subjects	Age of the subjects	Starting age of playing	Δ%[a] in sub-cortical area (SCA) and cortical area (CA)		
				Sites	SCA	CA
Ashizawa et al. [19], pQCT	16 tennis players:					
	10 women	20.1 ± 0.6	11.6 ± 0.9	Mid-radius	+18.8%	+13.5%
	6 men	20.2 ± 0.7	12.8 ± 1.5	Distal radius	+6.8%	nm
Haapasalo et al. [20], pQCT	12 male former top-level tennis players	29.8 ± 4.8	9.8 ± 3.0	Proximal humerus	+18.5%	+11.7%
				Humeral shaft	+0.8% (ns)	+26.3%
				Distal humerus	−3.3% (ns)	+31.9%
				Radial shaft	+28.6%	+14.8%
				Distal radius	+28.1% (ns)	+11.5%
Kontulainen et al. [23], pQCT	64 female tennis/squash players:					
	Young starters (n = 36)	26.5 ± 8.0	10.5 ± 2.2	Humeral shaft	ns	+20%
				Distal radius	Not given	+9%
	Old starters (n = 28)	44.4 ± 10.5	26.4 ± 8.0	Humeral shaft	ns	+7%
				Distal radius	Not given	+7%
Bass et al. [27], MRI	47 female tennis players:					
	Prepubertal (n = 17)	10.4 ± 0.3	5.7 ± 0.4	Mid-humerus	+3.3% (ns)	+7.7%
				Distal humerus	−0.7% (ns)	+11.2%
	Peripubertal (n = 11)	12.2 ± 0.3	6.5 ± 0.6	Mid-humerus	+3.6% (ns)	11.9%
				Distal humerus	−4.7% (ns)	+16.5%
	Postpubertal (n = 19)	14.5 ± 0.4	7.1 ± 0.4	Mid-humerus	−1.9% (ns)	+12.1%
				Distal humerus	−8.9%	+14.5%

All side-to-side differences were significant, except those mentioned with ns. ns: non significant; nm: not measured.
[a] Δ% = (Dominant − Nondominant) / Nondominant × 100.

by the increase in total bone size. With regard to this hypothesis, tennis playing would be most profitable for bone structural rigidity during early childhood [27].

It must be noted that the asymmetry in cortical volume was four times greater in the one-handed backhand players than in the two-handed backhand players, reaching statistical significance in the first group only ($P < 0.05$). No difference was found between men and women, suggesting that there was no gender effect in this result. It seems that the one-handed backhand technique, by inducing higher loads on the dominant forearm [39], had a greater impact on cortical volume.

No biomechanical indices reflecting torsional or bending rigidity were calculated in our study. Such indices are dedicated to the diaphyses, which are characterized by a hollow cylindrical shape. Estimating the bone strength at the noncylindrical epiphyses, containing both trabecular and cortical bone, is more challenging.

The predominant factor that determines bone adaptative response to loading is still debated. In the context of the mechanostat theory, the magnitude of the skeletal adaptative response varies according to the "change" in mechanical strain history [18]. Our results confirmed that grip strength is closely related to radial BMC or BMD, as previously shown [47–50]. These findings support the concept of the muscle–bone unit, stating that the largest voluntary loads applied to load-bearing bones come from muscle forces [24,51]. Hitting the tennis ball involved several muscles including the pronator teres and the brachioradialis [14], which display large insertions on the distal radius. The correlations we found between muscle strength and the bone parameters were still significant after controlling for body size, indicating that the muscle–bone relationship was not only due to the fact that genes regulating size act on both tissues. Even if correlation does not necessarily imply causation, it is widely admitted that the size and shape of skeletal elements are strongly influenced by muscle activity [18,52–54]. Causal associations between muscle activity and skeletal shape have been shown for extreme cases, such as congenital muscle paralysis [53] or recovery after injury [55].

Interestingly, athletes displayed lower correlations between muscle strength and BMD than nonathletes [56–58], as if mechanical loading altered the muscle–bone relationship. In the present study, adjustment of BMC for muscle volume revealed that there was more bone mineral mass for a given muscle volume in the dominant radius. These findings were also true after adjustment for grip strength, being in accordance with previous data on a largest sample [59]. These results suggest that other factors than muscle forces contribute to the bone response during growth. This hypothesis was recently reinforced by Daly et al. [29], who found that the asymmetry in muscle area only accounted for 11.8–15.9% of the variance of the asymmetry in humeral bone mass, bone size and bending strength. Likewise, Janz et al. [60] highlighted that the association they observed between everyday activity and bone geometry in children could not be solely explained by lean mass. Frost and

Schoenau [61] thought that variations in muscle forces acting on bone apparently explain upwards of 50% of the postnatal variability in development of bone strength and mass. Heinonen et al. [32] found a positive correlation between muscle area and cortical area in the anterolateral sector of the tibia but not in the anteromedial and posteromedial sectors of the bone.

The bone response to loading was site-specific probably because of the complexity of the forces applied to the bone. Among these forces, some stimuli could exert an additional effect on bone tissue without affecting the muscles, maybe through the vibrations associated with tennis playing [29,59] or through impacts (e.g., gymnastics, jumps). Fastening strain gauge type sensors on the skin of tennis players, some authors found wrist and elbow vibratory accelerations of 6.81 and 1.53 g, respectively ($g = 9.81\ \mathrm{m{\cdot}s^{-2}}$) for center ball impacts [12]. This result suggests that the distal radius may be particularly exposed to racket vibrations [34]. Nikander et al. [3] found higher values in the section modulus (reflecting bone strength against bending) at the femoral neck in women practicing high-impact or odd-impact loading sports rather than nonimpacts sports. Neural adaptations and improvements in the muscular excitation–contraction coupling, improving muscle strength without any change in muscle mass, could also have influenced the bone response to loading [29]. Likewise, the rate of force development and the pattern of muscle activation may play a role.

Total bone volume and cortical volume were not different between both radii after adjustment for muscle volume, as if there was a well-coordinated interaction of muscle activity and geometric architectural adaptation. From the point when the increase in bone geometry has fitted with the increase in muscle volume in response to loading, the extra bone mineral mass might have been used to improve bone density. The slightly higher vBMD we observed at the dominant distal radius could reflect the specific behavior of the epiphyses in response to loading, since previous studies have shown an increase in vBMD at distal sites containing both cortical and trabecular bone [19,22,23]. We did not find any correlation between the asymmetries in bone geometry and in muscle volume, preventing us to conclude that exercise-induced increase in muscle volume leads to a proportional increase in bone volume. The absence of correlation could be due to the small sample size or to the distal position of the skeletal site, where muscle volume was measured by tracing several distinct regions of interest. Indeed, positive correlations between muscle and bone asymmetries have been found at the humeral diaphysis, where the humerus and surrounding muscle groups could be encompassed within one region of interest [29].

This study demonstrated that impact-loading physical activity, when started during childhood, improved the mechanical competence of the loaded bones through geometrical changes. It remains a challenge to identify the factors involved in triggering the bone mineral accrual at loaded sites, given the complexity of the mechanical environment of the bone. Muscle forces as well as muscle-independent mechanical stimuli, all being specific of the activity, seem to play a major role in bone response to loading.

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