Effects of Long-Term Tennis Playing on the Muscle-Bone Relationship in the Dominant and Nondominant Forearms

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Abstract/Résumé

The relationship between muscle strength and bone mineral density illustrates the positive effect of mechanical loading on bone. But local and systemic factors may affect both muscle and bone tissues. This study investigated the effects of long-term tennis playing on the relationship between lean tissue mass and bone mineral content in the forearms, taking the body dimensions into account. Fifty-two tennis players (age 24.2 ± 5.8 yrs, 16.2 ± 6.1 yrs of practice) were recruited. Lean tissue mass (LTM), bone area, bone mineral content (BMC), and bone mineral density were measured at the forearms from a DXA whole-body scan. Grip strength was assessed with a dynamometer. A marked side-to-side difference (p < 0.0001) was found in favor of the dominant forearm in all parameters. Bone area and BMC correlated with grip strength on both sides (r = 0.81–0.84, p < 0.0001). The correlations were still significant after adjusting for whole-body BMC, body height, or forearm length. This result reinforced the putative role of the muscles in the mechanical loading on bones.

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In addition, forearm BMC adjusted to LTM or grip strength was higher on the dominant side, suggesting that tennis playing exerts a direct effect on bone.

La relation entre force musculaire et densité minérale osseuse illustre l’effet positif des contraintes mécaniques sur le tissu osseux. Mais certains facteurs locaux et systémiques sont susceptibles d’affecter aussi bien le tissu musculaire que le tissu osseux. Le but de ce protocole était d’étudier les effets de la pratique du tennis sur la relation entre la masse maigre et le contenu minéral osseux des avant-bras, en tenant compte des dimensions corporelles. Cinquante-deux joueurs de tennis, âgés de 24.2 ± 5.8 ans, ayant pratiqué pendant 16.2 ± 6.1 ans, ont été recrutés. La masse maigre (LTM), la surface osseuse, le contenu minéral osseux (BMC), et la densité minérale osseuse (BMD) ont été mesurés sur les avant-bras, à partir du scan du corps entier obtenu par DXA. La force musculaire de préhension a été évaluée à l’aide d’un dynamomètre. Une différence marquée a été observée entre les avant-bras (p < 0.0001) au bénéfice du côté dominant, et ce pour tous les paramètres. La surface osseuse et BMC sont corrélés à la force musculaire de préhension des deux côtés (r = 0.81–0.84, p < 0.0001). Les corrélations étaient toujours significatives après ajustement au BMC du corps entier, à la taille, ou à la longueur des avant-bras. Ce résultat confirmerait l’hypothèse selon laquelle les muscles exercent des contraintes mécaniques sur les os. De plus, BMC ajusté à LTM ou à la force musculaire de préhension était supérieur sur l’avant-bras dominant, ce qui suggère que la pratique du tennis exerçait un effet direct sur les os de l’avant-bras.

Introduction

If skeletal development is mainly under strong genetic influence, other factors may play a crucial role in bone mineral acquisition, especially during childhood and adolescence. Mechanical loading has been considered as the predominant influence on bone mineral acquisition throughout life. The nonmechanical agents, such as hormones and nutritional and lifestyle factors, are thought to modulate the bone response to mechanical loading (Frost, 2000; Schoenau and Frost, 2002).

Results concerning the effects of tennis playing on bone mineral content (BMC) or bone mineral density (BMD) on the upper limbs support this view. Large side-to-side differences in BMC and BMD have been reported between the dominant and nondominant upper limbs (Haapasalo et al., 1996; Kannus et al., 1994; 1995; Kontulainen et al., 1999; 2002). In this model the genetic, hormonal, and nutritional factors which influence bone remodeling are similar for both sides. As a consequence, the greater BMC and BMD observed at the dominant side are attributed to the unilateral loading involved during tennis playing.

Mechanical loading may stimulate bone formation through different modalities. Vibrations due to the impact of the ball on the racket could play a role in the bone response at the dominant side. This hypothesis has been suggested in tennis players (Todorov, 1975). But measuring mechanical vibrations of bone in vivo remains a challenge.

The composition of the tissue surrounding bones may also play a role. The muscles must be considered as masses of tissue attached to the bones. In this respect they might exert a positive effect on weight-bearing bones when gravity is taken into account. Fat mass could exert the same effect. However, its influence is probably negligible when examining the non-weight-bearing bones of the upper limbs.
The marked increase in BMC and BMD at the dominant extremity in tennis players might be partly due to the higher muscular activity (Calbet et al., 1998; Kannus et al., 1994). Tsuji et al. (1995) found a positive correlation between grip strength and BMD at the midradius, but only on the dominant side. Likewise, several researchers reported a positive association between grip strength and adjacent BMC or BMD in sedentary adults (Beverly et al., 1989; Sandler et al., 1989; Sinaki et al., 1989). Such results were in accordance with the hypothesis of the uppermost role played by muscular contractions in bone formation (Frost, 2000).

But muscle strength had also been shown to correlate with BMD at unrelated sites (Kritz-Silverstein and Barrett-Connor, 1994; Nordström et al., 1995). As genes regulating size are likely to influence both muscle and bone tissues (Seeman et al., 1996), it could be assumed that the association between muscles and bones is systemic rather than local. Other stimuli, such as androgen levels, may also have independent effects on both tissues, contributing to this general association (Slemenda, 1995).

As a result, the relationship between muscle strength and BMD seems to be more complex than would be predicted from a simple consideration of direct muscle attachments to bone (Blimkie and Högler, 2003; Snow-Harter et al., 1990). The cause-and-effect relationship between muscular activity and bone accrual cannot be established by simple correlations (Burr, 1997). Tennis playing is an interesting model by which to study the relationships between muscle and bone tissues with (dominant upper limb) or without (nondominant upper limb) an intensive mechanical loading. Side-to-side comparisons can help us understand the mechanisms by which long-term-unilateral loading affects muscle and bone tissue.

Our objective was to study the effects of long-term tennis playing on the relationship between muscle strength, lean tissue mass, BMC, and BMD, measuring the parameters at the same region of interest, i.e., the forearms. We examined the dependence of the muscle-bone relationship on the body dimensions and the degree of mechanical loading (dominant vs. nondominant forearms).

Materials and Methods

SUBJECTS

Fifty-two regional-level tennis players (28 men and 24 women, all Caucasian) participated in this study. All had been practicing tennis for at least 5 years and were still playing tennis at the time of the experiments. Twenty-six of the players used both hands for backhand stroke (8 men, 18 women), the others used only the dominant hand. None of the players had any disease or had ever used medication known to affect the bones. Any player who had experienced a fracture of the hand or forearm bones was excluded from the study. Informed written consent was obtained from each participant. The study was approved by the regional Human Ethics Committee of the University of Tours, France.

PROTOCOL

*Anthropometric Measurements.* Body weight (in kg) was measured on a balance-beam scale (SECA 709, Hamburg, Germany) with 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, Germany).

**Bone Mineral and Body Composition Measurements.** Bone area (in cm²), bone mineral content (BMC, in g), bone mineral density (BMD, in g·cm⁻²) and lean tissue mass (LTM, in g) were determined by dual-energy X-ray absorptiometry (Delphi QDR® Series, Hologic Inc., Waltham, MA). A region of interest was derived from the whole-body scan which was defined as the area between the proximal end of the olecranon and the end of the fingers. From this region, bone area, BMC, BMD, and LTM of the forearm and hand were derived. Those parameters will be referred to as “forearm parameters” even if all the measurements took the hand into account. All analyses were performed by the same technician in order to minimize interobserver measurement variation. The placement of the region of interest was tested for reproducibility, based on two repeated analyses of seven data sets and evaluated by the root-mean-square coefficient of variation (Glüer et al., 1995). The coefficient of variation was 0.11% for LTM, 0.83% for BMC, and 0.67% for BMD.

**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 was calculated according to the formula given by Glüer et al. (1995). Two repeated measurements were made with each weight. The 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 to 90° and the forearm in a midprone 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 the right and left hand, beginning with the right hand. Each trial was followed by a 30-second 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 4.67% for dominant grip strength and 3.69% for nondominant grip strength.

**Training History.** Training history was assessed by a questionnaire specifically designed for this study. The participants recorded the starting age of regular tennis playing of at least 1 hour a week and the number of years they had been practicing. For each year, they were asked to approximate the number of hours per week they played tennis. Hence the total training time (total amount of training hours) was calculated for each player during the entire career, taking into account any breaks due to injuries or holidays and the seasonal differences in playing time.

**Statistical Analysis**

All the data are shown as mean ± standard deviation. The normality of the parameters was tested by the Kolmogorov-Smirnov test. The background characteristics were compared between men and women with a student t-test. The parameters measured at the dominant and nondominant arms were compared using a parametric paired t-test. One-way Anova for paired samples was used to compare the side-
to-side differences in grip strength, forearm LTM, bone area, BMC, and BMD between men and women, and between one-handed and two-handed backhand players. Side-to-side difference was expressed as percentage of the nondominant value (Δ% = (dominant – nondominant) / nondominant × 100).

Associations between grip strength, LTM, bone area, BMC, and BMD on both sides were tested by the Pearson product-moment correlation coefficient. The same method was applied in order to detect associations between training history parameters and side-to-side differences in grip strength, LTM, bone area, BMC, and BMD. Simple linear regression was used to analyze the relationships linking bone parameters to LTM or grip strength. Then the slopes of the regression lines were compared between both forearms. The Z-test of correlation was used to test the association between two variables while maintaining a third variable (called the co-factor) constant. This test eliminates the influence of the co-factor on both variables.

**Results**

The characteristics of the subjects are given in Table 1. The men were older than the women and had more years of tennis playing practice. They were also taller and heavier. They showed a lower percentage of fat mass and a higher whole-body BMD (p < 0.001).

LTM, bone area, BMC, BMD, and grip strength at each forearm, as well as the side-to-side difference, are listed in Table 2. LTM, bone area, BMC, BMD, and grip strength were significantly higher at the dominant forearm (p < 0.0001). The players who used only the dominant hand for backhand stroke did not show a greater side-to-side difference in muscle and bone parameters than the players who used both hands.

<table>
<thead>
<tr>
<th>Table 1 Characteristics of the Subjects</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Women (n=24)</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>Age (yrs)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>Fat mass (%)</td>
</tr>
<tr>
<td>Whole body BMD (g·cm⁻²)</td>
</tr>
<tr>
<td>Starting age of playing (yrs)</td>
</tr>
<tr>
<td>Years of playing</td>
</tr>
<tr>
<td>Total training time (hrs)</td>
</tr>
</tbody>
</table>

*Note:* BMD = bone mineral density. Difference between men and women: ** p < 0.01; *** p < 0.001
No difference was found between men and women in terms of asymmetries in grip strength, forearm LTM, bone area, BMC, and BMD, even after adjusting for age or number of years playing tennis.

The results of the correlation analysis between grip strength, LTM, and bone parameters at both forearms are given in Table 3. The correlations between grip strength and forearm bone area, BMC, or BMD on both sides were no longer significant, with forearm LTM as a co-factor.

Whole-body BMC, height, and forearm length reflect body dimensions. We separately introduced these parameters as co-factors in order to test the dependence of the correlations presented in Table 3 on body size. All correlations remained significant when the whole-body BMC was introduced as a co-factor, except the correlations with BMD. The introduction of height or forearm length as co-factors lowered the correlations but they all remained significant. Adjusting the correlations for age or number of years playing tennis did not change the results.

In order to compare the relationships between grip strength and forearm BMC at each side, we used simple linear regressions. As shown in Figure 1, the slopes of the regression lines were not significantly different between both forearms. Owing to this condition, an analysis of covariance could be performed. Forearm BMC adjusted for grip strength was higher at the dominant forearm than at the nondominant forearm ($p < 0.05$). The same result was obtained when forearm BMC was adjusted for forearm LTM (Figure 2). For a given grip strength or a given forearm LTM, forearm BMC was higher at the dominant side. The results were similar when forearm BMC was replaced by forearm BMD.

The data of both forearms were pooled in order to compare the muscle-bone relationship between men and women. When adjusted for LTM, forearm BMC was greater in women than in men ($p < 0.05$). This difference was no longer significant when investigating each forearm separately.

### Table 2 Variables in the Dominant and Nondominant Forearms of the Tennis Players

<table>
<thead>
<tr>
<th>Variables</th>
<th>Dominant $M$</th>
<th>Dominant $SD$</th>
<th>Nondominant $M$</th>
<th>Nondominant $SD$</th>
<th>$\Delta%$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTM (g)</td>
<td>1313.1</td>
<td>333.8</td>
<td>1143.4</td>
<td>294.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Bone area (cm²)</td>
<td>119.1</td>
<td>24.7</td>
<td>106.3</td>
<td>22.6</td>
<td>12.4</td>
</tr>
<tr>
<td>BMC (g)</td>
<td>89.9</td>
<td>23.4</td>
<td>75.7</td>
<td>21.0</td>
<td>19.8</td>
</tr>
<tr>
<td>BMD (g·cm⁻²)</td>
<td>0.747</td>
<td>0.051</td>
<td>0.703</td>
<td>0.058</td>
<td>6.5</td>
</tr>
<tr>
<td>Grip strength (N)</td>
<td>602.7</td>
<td>155.7</td>
<td>521.1</td>
<td>128.5</td>
<td>15.7</td>
</tr>
</tbody>
</table>

Note: LTM = lean tissue mass; BMC = bone mineral content; BMD = bone mineral density. Relative side-to-side differences ($\Delta\%$) are expressed in percentage of nondominant value.

a $\Delta\% = (\text{Dominant} - \text{Nondominant}) / \text{Nondominant} \times 100$

† dominant $>$ nondominant, $p < 0.0001$
The potential relationships between the muscle and bone asymmetries and the training history parameters were examined. Neither the side-to-side difference in grip strength nor the side-to-side difference in forearm LTM correlated with any of the training parameters. On the contrary, there was a positive correlation between the side-to-side difference in forearm LTM and forearm bone area or BMC ($r = 0.44$, $p < 0.01$). The side-to-side difference in bone area was the only parameter that correlated with the starting age of playing ($r = -0.29$, $p < 0.05$). No correlation was found between the total training time or the number of years playing tennis and any of the bone or muscular asymmetries.

### Discussion

In this study, grip strength, LTM, and BMC were closely correlated in the forearms of tennis players. The relationships remained significant when body dimensions were taken into account. These results point to a relationship between bone formation and muscular activity, although it could not be considered as direct evidence for a causal relationship. Furthermore, BMC adjusted for LTM or grip strength was higher at the dominant forearm. This result suggests that, in addition to the effect mediated by the muscles, tennis playing has a positive impact on bone tissue that is independent of muscle mass or muscle strength. These findings contribute to the understanding of the mechanisms that explain the greater BMC in a tennis player’s dominant arm. They illustrate the important, but seemingly limited, role of muscles in the mechanical loading-induced bone response during tennis playing.

### Table 3 Pearson Product-Moment Correlation Coefficients Between Variables at the Dominant and Nondominant Forearms of the Tennis Players

<table>
<thead>
<tr>
<th></th>
<th>LTM (g)</th>
<th>Bone area (cm$^2$)</th>
<th>BMC (g)</th>
<th>BMD (g·cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dominant Forearm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grip strength (N)</td>
<td>0.87</td>
<td>0.82</td>
<td>0.81</td>
<td>0.65</td>
</tr>
<tr>
<td>Adjusted to whole-body BMC</td>
<td>0.59</td>
<td>0.35*</td>
<td>0.33*</td>
<td>0.05 (ns)</td>
</tr>
<tr>
<td>LTM (g)</td>
<td>–</td>
<td>0.92</td>
<td>0.91</td>
<td>0.71</td>
</tr>
<tr>
<td>Adjusted to whole-body BMC</td>
<td>–</td>
<td>0.47***</td>
<td>0.33*</td>
<td>–0.11(ns)</td>
</tr>
<tr>
<td><strong>Nondominant Forearm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grip strength (N)</td>
<td>0.89</td>
<td>0.84</td>
<td>0.84</td>
<td>0.67</td>
</tr>
<tr>
<td>Adjusted to whole-body BMC</td>
<td>0.67</td>
<td>0.51***</td>
<td>0.49***</td>
<td>0.12 (ns)</td>
</tr>
<tr>
<td>LTM (g)</td>
<td>–</td>
<td>0.91</td>
<td>0.91</td>
<td>0.76</td>
</tr>
<tr>
<td>Adjusted to whole-body BMC</td>
<td>–</td>
<td>0.55</td>
<td>0.52</td>
<td>0.16 (ns)</td>
</tr>
</tbody>
</table>

*Note:* All correlations statistically significant at $p < 0.0001$, except: *$p < 0.05$; ***$p < 0.001$; (ns) = nonsignificant.
Figure 1. Relationships between grip strength and forearm bone mineral content (BMC) in the dominant and nondominant forearms of the tennis players.

Figure 2. Relationships between forearm lean tissue mass (LTM) and bone mineral content (BMC) in the dominant and nondominant forearms of the tennis players.
The comparison of bone parameters between the forearms revealed a marked asymmetry in the tennis players. We observed 20% greater BMC in the dominant forearm, which was slightly higher than the values reported in the literature. It must be noted that Pirnay et al. (1987), in a group of 10 players, found 34% greater BMC at the distal radius and 25% greater BMC at the midradius. Unlike the present study, their subjects were not only professionals but were also strictly one-handed backhand players, which probably explained why Pirnay et al. found such great asymmetries.

Some authors have reported a side-to-side difference in radial BMC less than 15% (Haapasalo et al., 2000; Kannus et al., 1994; 1995; Kontulainen et al., 1999; 2001). In most of the previous studies based on dual-energy x-ray absorptiometry, the bone measurements were made at a diaphyseal or a distal site of the radius (Haapasalo et al., 2000; Kannus et al., 1994; 1995; Kontulainen et al., 1999; 2001) or the ulna (Kannus et al., 1994). We measured the bone parameters at the forearm (i.e., radius and ulna) and hand. It has been shown that playing tennis slightly increases the length of bones in the upper limb (Krahl et al., 1994). Thus, our region of interest may be longer at the dominant side, hence increasing the difference in BMC between both forearms.

We noted a small side-to-side difference in forearm BMD (6.5%). Kannus et al. (1994) found a 10% difference at the diaphyseal and distal radius and a lower difference at the ulnar shaft (3.1%) and distal ulna (6.3%). The smaller difference observed in our study might be due to the fact that we measured both ulna and radius.

Most of the previous studies showed a larger asymmetry in the arms of tennis players compared to sedentary subjects (Buskirk et al., 1956; Haapasalo et al., 1996; Kannus et al., 1994; 1995). Despite the absence of a control group, the unilateral loading is likely to explain the largest part of the side-to-side difference we observed in bone parameters. However, matched controls would allow for a better comparison of covariates.

Soft tissue surrounding bones may exert a positive effect on the accrual of bone mass. Indeed, the gravitational forces due to muscle mass are likely to be osteogenic when applied to weight-bearing bones. Calbet et al. (1998) found a positive correlation between LTM (close to muscle mass) and BMC in the dominant arm of 9 tennis players. Fat mass, which is inert in comparison with muscle mass, has also been identified as a determining factor of BMD, in women (Reid et al., 1992) and men over 65 years of age (Pluijm et al., 2001).

In addition to the role played by body composition, muscle strength is another determinant of mechanical loading (Taaffe et al., 2001). Several researchers have suggested that the higher muscular activity in the dominant limb may partly explain higher BMC (Calbet et al., 1998; Kannus et al., 1994). Indeed, the muscles induce mechanical stress on bones and tendons during muscular contraction.

Grip strength could be considered as a noninvasive and easy-to-measure indicator of muscular stress on forearm bones. Gripping the racket is necessary during tennis playing. Since the handgrip device kept the forearm in position, variability between the three trials of grip strength was probably due to motivational aspects. The asymmetry in grip strength was slightly smaller in this study compared to previous reports of 18 to 24% in adults (Haapasalo et al., 1994; 2000; Kannus et al., 1994; 1995; Kontulainen et al., 1999; 2001).
Grip strength correlated positively with forearm bone area, BMC, and BMD in the tennis players. These findings are in accordance with results found by Tsuji et al. (1995) in young wrestlers and basketball players. Positive correlations between grip strength and radial BMD or BMC have also been reported in postmenopausal women (Sandler et al., 1989; Sinaki et al., 1989).

To our knowledge, the relationship between muscle strength and bone parameters has rarely been examined in tennis players. Calbet et al. (1998) found a correlation between leg extension strength and Ward’s femoral BMD. Tsuji et al. (1995) observed a correlation between grip strength and midradius BMD on the dominant side ($r = 0.43, p < 0.05$). The grip strength/BMD correlations we found were slightly stronger than those reported in the aforementioned studies. From an anatomical point of view, the region of interest (forearm and hand) we analyzed corresponds to the muscles involved in gripping. Measuring the BMD at a local site on the radius could have led to an underestimation of the correlation between grip strength and bone parameters.

We failed to find any correlation between the asymmetry in grip strength and the asymmetry in any of the bone parameters. Among those who have looked for such a correlation (Haapasalo et al., 1994; 1998; Kannus et al., 1994; 1995), only Haapasalo et al. (1994) reported that the asymmetry in elbow flexion strength correlated with the asymmetry in the humeral BMC and BMD in squash players. Burr (1997) stated that a close relationship between muscle strength and bone parameters does not necessarily imply a direct cause-effect relationship. Genes have been suspected to be responsible for the interaction between bone and muscle systems (Li et al., 2001; Seeman et al., 1996). Several factors may influence the growth of both skeletal and muscle tissues, including growth hormone and androgen levels as well as physical activity (Slemenda, 1995). All these factors play a crucial role in skeletal growth and the determination of body dimensions. In addition, muscle strength has been shown to correlate with BMD at unrelated sites (Kritz-Silverstein and Barrett-Connor, 1994; Nordström et al., 1995). Such correlations could be due to the co-contraction of synergistic muscles, explaining why mechanical strains could be applied to bones which are far from the anatomic region where the muscular contraction was originally initiated. However, the relationship between muscle and bone may be explained rather by systemic factors.

The correlations between grip strength and forearm LTM and BMC remained significant after taking whole-body BMC, height, or forearm length into account. After adjustment for these variables, BMD and the muscular parameters were no longer correlated because BMD (BMC divided by bone area) is already normalized to body size. We can infer from this result that local mechanical loading reinforces the existing association between grip strength and forearm LTM and BMC. It seems that the body dimensions cannot solely explain this association.

The women displayed a higher forearm BMC than the men for a given LTM. This result is in accordance with previous findings concerning whole-body BMC (Ferretti et al., 1998; Schiessl et al., 1998). Ferretti et al. (1998) and Schiessl et al. (1998) suggested that estrogens could affect bone sensitivity to mechanical loading by lowering the remodeling threshold.

In the tennis players, the side-to-side difference in forearm BMC was no longer significant with forearm LTM as a covariate, suggesting that muscles take
part in the bone response to physical activity. In addition, grip strength and forearm BMC were no longer correlated when forearm LTM was introduced as a co-factor. So the muscles may act as a mediator in the relationship between grip strength and forearm BMC. It supports the concept of the muscle-bone unit (Frost, 2000). Schoenau and Frost (2002) proposed that “the largest voluntary loads applied on load-bearing bones come from muscle forces, not body weight” (p. 406). This theory can all the more be applied to the forearm since it is a non-weight-bearing site. The exact mechanisms through which muscular exercise exerts an effect on bone formation are still debated.

Nordström et al. (1996) estimated that quadriceps strength was the best significant predictor of BMD of the tibial tuberosity in young recreational ice-hockey players, whereas it was not in high-level players of the same age. They suggested there may be a threshold above which additional muscle strength has no impact on BMD. Alfredson et al. (1996; 1997) found correlations between muscle strength and local BMD in sedentary subjects, but not in soccer and volleyball players. In other studies, a 1-year unilateral strength training program markedly improved muscle strength in the trained limb whereas the increase in BMD was nonsignificant (Vuori et al., 1994) or even absent (Heinonen et al., 1996). As a consequence, the association between the gain in muscle strength and the change in BMD has not been fully established (Blimkie et al., 1996; Friedlander et al., 1995; Morris et al., 1997). It is known, however, that muscle strength can be improved through neural adaptations, without any increase in muscle mass. Moreover, the training effects may be delayed in the bone tissue compared to the muscle tissue. Lohman et al. (1995) reported a 2% increase in BMD after 18 months of strength training. Sievänen et al. (1996) reported that after the rupture of the anterior cruciate ligament, one woman experienced a 25% decrease in the BMD of her patella. She eventually recovered 100% of the BMD of the patella one year after her leg extension strength had returned to normal.

The observations reported by Sievänen et al. (1996) strongly support the theory of the functional relationship between muscular activity and BMD. Although a genetic factor is undoubtedly involved in the muscle-bone relationship, these two tissues seem to be functionally associated, since in Sievänen et al.’s study BMD was dependent on muscular activity. In this regard muscle strength, rather than muscle mass, appears to be the important contributing factor to BMD.

In addition to the role of muscles, it seems that impact-loading increases BMD more effectively than non-weight-bearing activities. Indeed, swimmers showed higher lean body mass but similar whole-body BMD than sedentary subjects (Courteix et al., 1998). Fehling et al. (1995) found that athletes who participated in impact-loading sports such as volleyball and gymnastics displayed higher BMD than athletes in active-loading sports such as swimming.

BMC adjusted for LTM or grip strength was higher in the dominant forearm of the tennis players in the present study. This result means that, for a given LTM or grip strength, BMC was greater in the dominant forearm, suggesting that tennis playing exerts an effect on bone tissue that is independent of muscular contractions. This effect could be attributed to the mechanical vibrations created by the impacts of the ball on the racket (Todorov, 1975).

Heinonen et al. (2001) measured the ground reaction forces in an extreme
impact-loading sport, the triple jump. They found a significant relationship between triple jumpers’ lower limb bone size and the weight-adjusted loading characteristics of the body. To date, no attempt has been made to correlate loading characteristics and bone size in the dominant arm during tennis playing. Hennig et al. (1992) used skin-fastened strain gauge sensors above the ulnar head and the lateral epicondyle of the humerus to measure the vibrations experienced by the body during tennis playing. Wrist and elbow accelerations were 6.81 and 1.53 g, respectively (g = 9.81 m·s−2) for center ball impacts. Accelerations were three times higher for off-center ball impacts. Several factors are likely to modulate the mechanical vibrations encountered by each player including his or her technique, the morphology of his/her arm, the racket, the velocity and the location of impact. In addition, Hennig et al. (1992) suggested that the muscles and other soft tissues may damp these mechanical vibrations. If this hypothesis is true, it means that the effects of vibrations on bone would be reduced. Unfortunately, Hennig et al. did not examine bone size and BMD.

We did not evaluate training intensity in the present study. The average number of strokes during a training session, as well as the intensity of the stroke, depend on the player’s characteristics. The estimation of training intensity would have enabled a better understanding of the complex mechanisms linking the biomechanical factors to bone mass accrual.

This study supported existing reports of a relationship between muscle strength, muscle mass, and bone density. The association between muscle and bone tissues has been attributed either to local or systemic mechanisms (Sahin et al., 2002). In this study it was clear that tennis playing induces local mechanical strains on the dominant forearm, increasing bone area, BMC, and BMD at the playing side. The side-to-side difference could be partly explained by muscle contractions. Bone accrual may also be stimulated by the mechanical vibrations transmitted to forearm bones. This effect seems to be independent of muscular activity. The results of the study confirm the crucial role played by local mechanical loading in bone formation, either mediated by the muscles or directly applied to the bones.

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References


