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ORIGINAL ARTICLE

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# Short-term and long-term site-specific effects of tennis playing on trabecular and cortical bone at the distal radius

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**Abstract** Mechanical loading during growth magnifies the normal increase in bone diameter occurring in long bone shafts, but the response to loading in long bone ends remains unclear. The aim of the study was to investigate the effects of tennis playing during growth at the distal radius, comparing the bone response at trabecular and cortical skeletal sites. The influence of training duration was examined by studying bone response in short-term (children) and long-term (young adults) perspectives. Bone area, bone mineral content (BMC), and bone mineral density (BMD) of the radius were measured by DXA in 28 young (11.6 ± 1.4 years old) and 47 adult tennis players (22.3 ± 2.7 years old), and 70 age-matched controls (12 children, 58 adults) at three sites: the ultradistal region (trabecular), the mid-distal region, and the third-distal region (cortical). At the ultradistal radius, young and adult tennis players displayed similar side-to-side differences, the asymmetry in BMC reaching 16.3% and 13.8%, respectively ($P < 0.0001$). At the mid- and third-distal radius, the asymmetry was much greater in adults than in children ($P < 0.0001$) for all the bone parameters (mid-distal radius, +6.6% versus +15.6%; third-distal radius, +6.9% versus +13.3%, for BMC). Epiphyseal bone enduring longitudinal growth showed a great capacity to respond to mechanical loading in children. Prolonging tennis playing into adulthood was associated with further increase in bone mineralization at diaphyseal skeletal sites. These findings illustrate the benefits of practicing impact-loading sports during growth and maintaining physical activity into adulthood to enhance bone mass accrual and prevent fractures later in life.

**Key words** growth · unilateral loading · child · bone mineral density · forearm

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## Introduction

Weight-bearing physical activity during growth may be an effective strategy to prevent osteoporosis and related fractures later in life. It has been suggested that childhood may be an opportune developmental period to magnify the positive effects of loading on bone strength [1–6].

Many racket sports studies support this view. Based on a side-to-side comparison, these studies enabled eliminating the confounding effects of genetic, hormonal, and nutritional factors that are encountered in cross-sectional studies [7]. The bone response to tennis-induced mechanical loading has been well described with three-dimensional (3D) imaging techniques in adults [8–12] and in children [13]. During bone growth, the diaphyses, which consist mainly in compact bone, increase their bone diameter by periosteal mineral apposition on the outer surface of bone [14]. This adaptation increases bone strength and consequently decreases the risk of fracture at long bone diaphyses.

Fracture of the distal radius and/or ulna is the most common fracture in children and adolescents [15–17] and is also frequent in osteoporotic subjects [18]. Girls who sustained a distal forearm fracture were shown to have a lower bone mass than girls who did not, this trait being persistent even 4 years postfracture [19]. Even so, little attention has been given to bone responsiveness to loading at the epiphyseal growing sites, which contain a relatively high percentage of trabecular bone [5].

The objective of this study was to investigate whether tennis playing, when started during growth, would have positive effects on bone tissue at the distal radius, and more specifically at the epiphysis that endures longitudinal bone growth. The short-term effects of tennis playing were studied in children and compared to the effects observed in young adults after the completion of longitudinal bone growth.

## Materials and methods

### Subjects

Twenty-eight young (22 boys and 6 girls) and 47 adult (23 men and 24 women) tennis players were recruited in the vicinity of Orléans (France). Only children who had been playing at least twice a week during the past 2 years were included in the study. A minimum training history of 5 years, with at least two training sessions a week, was required from the adults to take part in the study. All the players were engaged in tennis competition on a regular basis. Occasionally, they may have practiced other sports, but not at a competitive level.

Twelve healthy children (10 boys and 2 girls), practicing swimming, and 58 sedentary adults (21 men and 37 women) were recruited as controls because they had never been engaged in any unilateral training.

Non-inclusion criteria were any past fracture at the radius as well as any medical treatment known to affect bone metabolism. Each participant as well as the parents of minor subjects gave their informed written consent before their inclusion in the protocol. The study was approved by the Ethics Committee of the Region of Tours and was therefore performed in accordance with ethical standards.

### 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. Sitting height (trunk length + head) was determined while the child remained seated on a 45-cm-high chair. Leg length was then computed by substracting sitting height from body height. Forearm length was measured from the styloid process of the ulna to the end of the olecranon with a flexible tape.

### Skeletal maturity and growth

Children's bone age was evaluated on a left wrist radiograph according to the method described by Greulich and Pyle [20]. Twenty-two bones of the hand, wrist, and forearm were compared to an atlas using the software Maturos (version 4.0; Serono, France, 2000).

In addition, advancement in longitudinal growth was evaluated by anthropometric measurements (height, sitting height, leg length, weight) and chronological age using the regression equations proposed by Mirwald et al. [21]. These equations allow computing a maturity offset, which gives the time lag (in years) before or after the predicted peak height velocity (PHV) of the child. This method offers the opportunity to determine whether the child has already reached his (her) predicted PHV (positive maturity offset) or not (negative maturity offset).

### Bone mineral measurements

Bone area (in $cm^2$), bone mineral content (BMC, in g) and bone mineral density (BMD, in $g \cdot cm^{-2}$) were determined by dual-energy X-ray absorptiometry (DXA, Delphi QDR Series; Hologic, Waltham, MA, USA). The parameters were measured at the dominant and nondominant radius. According to their respective trabecular bone content, three sites were defined along the mid- to distal region of the radius. The first region, termed ultradistal radius, consisted of a 1.5-cm band adjacent to the end plate of the radius; the second region, named one-third radius, consisted of a 2-cm band one-third of the distance between the ulnar styloid and the olecranon; and the last region, labeled mid-distal, comprised the residual distance between the two sites already mentioned (Fig. 1). The ultradistal radius comprises the epiphysis and the metaphysis, which endure longitudinal bone growth. The mid-distal and third-distal radius are diaphyseal sites.

The intraobserver reproducibility of BMD was calculated by two repeated measurements in seven different forearms by the root-mean-square (RMS) coefficient of variation [22]. The RMS coefficient of variation was 1.1%, 0.6%, and 6.7% for the ultradistal, mid-distal, and third-distal regions, respectively.

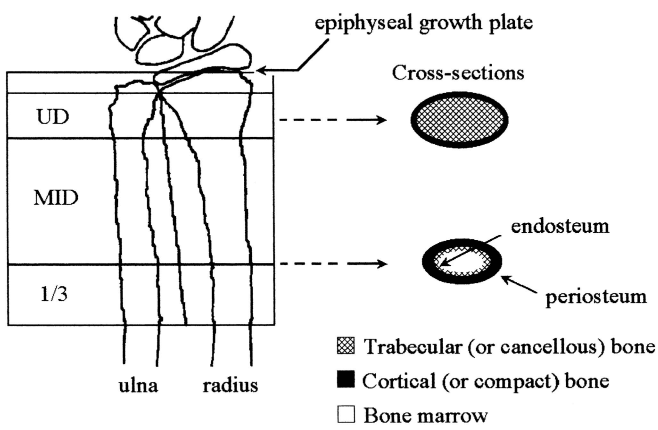


**Fig. 1.** Regions of interest at the distal radius and ulna, used to measure the bone area, bone mineral content, and bone mineral density in tennis players: *UD* (ultradistal), *MID* (mid-distal), and *1/3* (third-distal). The regions of interest were defined by the software supplied by the manufacturer (Delphi QDR series; Hologic, Waltham, MA, USA)

### Training history

The training history of the tennis players 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 breaks due to injuries or holidays. The children were helped by their parents to fill in the questionnaire.

### 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 side-to-side differences in bone area, BMC, and BMD were expressed as the percentage of the nondominant value ($\Delta_{\%}$ = (dominant − nondominant)/nondominant × 100). The bone asymmetry was compared between the tennis players and the control subjects with a one-way analysis of variance (ANOVA) for paired measurements. The dominant and nondominant values were compared within each group by a paired *t* test. One-way ANOVA for paired measurements was used to compare adult and young tennis players ("group" effect) in terms of bone asymmetry at each skeletal site ("dominant/nondominant" effect). In case of interaction between the two effects, bone asymmetry was compared between adults and children by a Student *t* test, and the dominant and nondominant forearms were compared in each group using a paired *t* test. The relationship between variables was tested by the Pearson product moment correlation coefficient.

## Results

### Characteristics of the subjects

The characteristics of the subjects are given in Table 1. The young players started playing tennis earlier than the adults but their tennis playing history was shorter ($P < 0.05$). The training time of the adults up to the age of 12 (mean age of the children's group) was 828 ± 878 h, which did not differ from the total training time of the children (893 ± 461 h). The maturity offset was −1.8 ± 1.2 years from PHV in the tennis players (range, −3.9 to +0.3 years) versus −0.7 ± 1.3 years from PHV in the young swimmers (range, −3.2 to +0.9 years). Only one child in the tennis group was supposed to have already reached his PHV at the time of the experiments (maturity offset = +0.3), versus five children in the control group.

The children's skeletal maturity at the beginning of tennis practice was unknown. However, the starting age of playing ranged from 3.7 to 8.4 years in girls and from 3.5 to 10.9 years in boys, which leads us to suggest that girls and boys were likely to be prepubertal or early pubertal when they started playing tennis.

**Table 1.** Characteristics of the tennis players and of the control subjects who have never practiced any unilateral sports

| | Tennis players | |
|---|---|---|
| | Children ($n$ = 28) | Adults ($n$ = 47) |
| Chronological age (years) | 11.6 ± 1.4 | 22.3 ± 2.7* |
| Bone age (years)[a] | 12.0 ± 1.7 | |
| Weight (kg) | 40.3 ± 10.3 | 66.0 ± 9.8* |
| Height (cm) | 149.8 ± 10.1 | 171.9 ± 7.8* |
| Fat mass (%) | 17.6 ± 5.4 | 18.4 ± 6.1 |
| Starting age of playing (years) | 6.7 ± 2.1 | 7.8 ± 2.3* |
| Years of playing | 5.0 ± 1.6 | 14.3 ± 3.6* |
| Total training time (hours) | 893 ± 461 | 3118 ± 2246* |
| | **Control subjects** | |
| | Children ($n$ = 12) | Adults ($n$ = 58) |
| Chronological age (years) | 12.2 ± 1.6 | 23.3 ± 3.2* |
| Bone age (years)[a] | 12.2 ± 1.9 | |
| Weight (kg) | 53.3 ± 11.8 | 62.6 ± 8.8* |
| Height (cm) | 162.6 ± 11.6 | 169.3 ± 8.2* |
| Fat mass (%) | 19.7 ± 8.7 | 23.3 ± 7.2 |

Values are means ± SD

[a] Bone age was evaluated on a left wrist radiograph according to the method described by Greulich and Pyle [20]

* Adults > children ($P < 0.05$)

### Side-to-side differences in the tennis players

In children, no significant difference was observed between the dominant and nondominant forearm lengths (21.6 cm on both sides). In adults, the respective values were 25.3 ± 1.6 cm and 25.0 ± 1.6 cm, with a significant side-to-side difference (+1.4%, $P < 0.0001$). Bone area, BMC and BMD on both sides for children and adults are given in Table 2. All the absolute values of bone area, BMC, and BMD are higher in adults than in children, on both the dominant and nondominant sides. BMD increased from the ultradistal radius to the third-distal radius, complying with the fact that the ultradistal radius is essentially trabecular (i.e., porous) whereas the third-distal radius is mainly composed of compact bone.

The side-to-side differences in bone densitometric parameters at each site of the radius are indicated in Table 2. No difference was found between adult and young players regarding bone area, BMC, and BMD asymmetries at the ultradistal radius. In contrast, the adult players showed a greater asymmetry in bone area, BMC, and BMD at the mid-distal and third-distal radius ($P < 0.05$, except for BMD at the mid-distal radius, where the difference was not significant).

Adjustment for the age of starting playing did not change the results concerning the comparison between adults and children in terms of bone area, BMC, and BMD asymmetries. After adjustment for the number of playing years, the children showed a greater asymmetry than the adults at the

**Table 2.** Bone area, bone mineral content (BMC), and bone mineral density (BMD) on the dominant and nondominant sides in adult and young tennis players, at the three regions of interest: ultradistal radius (UD), mid-distal radius (MID), and third-distal radius (1/3)

| | Children | | | Adults | | |
|---|---|---|---|---|---|---|
| | Dominant | Nondominant | $\Delta_{\%}$ [a] | Dominant | Nondominant | $\Delta_{\%}$ [a] |
| Bone area (cm$^2$) | | | | | | |
| UD | 3.18 ± 0.45 | 3.04 ± 0.47† | 4.9 | 3.82 ± 0.35 | 3.63 ± 0.34† | 5.4 |
| MID | 4.91 ± 1.43 | 4.73 ± 1.46† | **4.3** | 7.48 ± 1.43 | 6.72 ± 1.29† | **11.5***** |
| 1/3 | 2.44 ± 0.24 | 2.32 ± 0.24† | **5.5** | 2.92 ± 0.37 | 2.70 ± 0.33† | **8.2*** |
| BMC (g) | | | | | | |
| UD | 1.15 ± 0.31 | 0.99 ± 0.24† | 16.3 | 2.00 ± 0.36 | 1.75 ± 0.29† | 13.8 |
| MID | 2.18 ± 0.78 | 2.04 ± 0.72† | **6.6** | 5.00 ± 1.27 | 4.33 ± 1.06† | **15.6***** |
| 1/3 | 1.34 ± 0.22 | 1.26 ± 0.22† | **6.9** | 2.27 ± 0.43 | 2.00 ± 0.35† | **13.3***** |
| BMD (g·cm$^{-2}$) | | | | | | |
| UD | 0.356 ± 0.050 | 0.322 ± 0.037† | 10.6 | 0.521 ± 0.068 | 0.482 ± 0.058† | 8.0 |
| MID | 0.437 ± 0.037 | 0.427 ± 0.038† | 2.5 | 0.663 ± 0.069 | 0.640 ± 0.061† | 3.6 |
| 1/3 | 0.545 ± 0.049 | 0.539 ± 0.053† | **1.3** | 0.772 ± 0.069 | 0.736 ± 0.060† | **4.8**** |

Values are means ± SD
[a] $\Delta_{\%}$ = (Dominant − nondominant)/nondominant × 100
† Dominant > nondominant, $P < 0.0001$
**Bold***: $\Delta_{\%}$ adults > $\Delta_{\%}$ children, $P < 0.05$ (** $P < 0.01$; *** $P < 0.0001$)

ultradistal radius for the bone densitometric parameters. At the mid-distal and third-distal radius, the between-group difference concerning bone area, BMC, and BMD asymmetries disappeared.

Side-to-side differences were not compared between boys and girls because there were only 6 girls compared to 22 boys. In adults, men displayed greater asymmetry than women at the ultradistal and third-distal sites ($P < 0.05$) but the difference disappeared after adjustment for the number of playing years.

In the whole sample, a weak correlation was found between starting age of playing and the asymmetry in bone area at the ultradistal radius ($r = -0.28$, $P < 0.05$). Number of playing years correlated well with the asymmetry in bone area and BMC at the mid-distal radius ($r$ = 0.49 and 0.57, $P < 0.0001$) and with the asymmetry in bone area, BMC, and BMD at the third-distal radius ($r$ = 0.30, 0.55, 0.42, $P < 0.01$). Total training time correlated weakly with the asymmetry at the ultradistal site ($r = 0.23$ for bone area and BMC, $P < 0.05$). The correlation was stronger between total training time and the asymmetry in bone area and BMC at the mid-distal and third-distal radius ($r$ = 0.40–0.53, $P < 0.001$).

Most of these correlations were still significant when considering only the adult players, except the correlation between the number of playing years and the asymmetry in bone area at the mid- and third-distal radius. The sole correlations between playing history and bone asymmetry that were significant in the young tennis players were observed at the ultradistal radius. Notably, the asymmetry in BMD at the ultradistal radius correlated negatively with the starting age of playing in children (r = –0.40, $P < 0.05$).

### Side-to-side differences in the control group

Bone age was not significantly different between the young swimmers and the young tennis players. In the young swimmers, the BMD differences between the dominant and the nondominant forearms were not significant, whatever the site: 0.370 ± 0.053 versus 0.359 ± 0.059 g·cm$^{-2}$ (+3.8%, ns) at the ultradistal site, 0.487 ± 0.058 versus 0.490 ± 0.049 g·cm$^{-2}$ (–0.4%, ns) at the mid-distal radius, 0.623 ± 0.059 versus 0.615 ± 0.066 g·cm$^{-2}$ (+1.6%, ns) at the third-distal radius. Similar results were found for bone area and BMC.

In the sedentary adults, the asymmetries in BMD reached +0.8% at the ultradistal radius, –0.1% at the mid-distal radius, and +0.6% at the third-distal radius, and these were not significant. In both adults and children, all the side-to-side differences were greater in the tennis group than in the control group ($P < 0.05$).

## Discussion

The main findings of this study were that young tennis players, who started playing during pre- or early puberty, displayed a marked bone asymmetry between the dominant and nondominant radii at the ultradistal region, where longitudinal bone growth occurs. Moreover, the side-to-side difference observed in children was similar to that found in adults who experienced a much longer tennis practice. Conversely, bone asymmetry at the mid- and third-distal radius was larger in adults than in children, indicating further increase in bone mass accrual at diaphyseal sites when tennis playing was maintained into young adulthood.

Not all the asymmetries observed in the tennis players can be completely attributed to tennis playing, because a slight asymmetry has been reported in sedentary subjects [23–25]. However, the bone asymmetry was not significant in our control group and was much weaker than that found in tennis players, confirming previous findings [7,26–28].

In the young tennis players, the mid-distal and third-distal radius displayed a much lower asymmetry in BMC or BMD than the ultradistal radius. According to the findings of Schlenker and Von Seggen [29], the first two sites can be considered as cortical sites (even if they are not purely cortical) whereas the ultradistal site is mainly trabecular. It has been suggested that the time-course for adaptation or modeling thresholds may differ between trabecular and cortical bone [30]. In 7- to 17-year-old female players, BMD asymmetry observed at bone sites containing mainly cortical bone was not clearly larger in players than in sedentary subjects until Tanner stage 3 [28]. Since cortical bone is known to have a slower turnover than trabecular bone, its response to loading may require a longer period of training. The correlations we found between cortical asymmetry and number of playing years ($0.30 < r < 0.57$, $P < 0.01$) or total training time ($0.40 < r < 0.53$, $P < 0.01$) support this view.

It could be argued that the low asymmetry we observed in the young tennis players at cortical sites may also be caused by an increase in cortical porosity. The remove of calcium from within cortical bone would supply the calcium needed to achieve longitudinal skeletal growth [5,31]. However, this effect, if any, is probably more significant during the growth spurt. Because all the young tennis players included in this study (except one) still had not reached their PHV at the time of the experiments, a bone mass shift from the cortical diaphysis to the epiphyseal growth plate can hardly solely explain the discrepancies in bone response between the cortical and trabecular skeletal sites.

The fact that the radial length was not significantly different between both sides in the young tennis players does not mean that tennis playing does not affect longitudinal bone growth. Indeed, the asymmetry in bone length observed in adult players suggests that it does. The repetition of traction forces on the dominant forearm may partly explain this result. In addition, the diameter of the subclavian artery was shown to be 19% greater on the dominant side of tennis players [32], contributing to increase the blood flow and, thus, the disposal of local growth factors in the dominant arm.

Adults did not show a greater bone asymmetry at the ultradistal radius despite a longer tennis playing history. The side-to-side difference in densitometric parameters was even larger in children after adjusting for the number of playing years. These findings may be explained by a limited ability of the spongiosa to adapt to loading after the fusion of the epiphyses, which occurs at the end of adolescence. Conversely, adult players displayed a marked cortical asymmetry at the mid- and third-distal sites. In comparison to trabecular bone, cortical bone appeared to respond to loading by modelling during a longer period of time.

There are still controversies regarding the maintenance of exercise-induced benefits for bone tissue after detraining [33]. Our findings at the radial diaphysis at least highlighted that prolonging tennis playing into young adulthood was associated with further gain in bone mass, giving credit to the necessity of a long-term commitment to impact-loading sports.

If the fusion of the epiphyses limits the adaptation of the spongiosa to loading, practicing impact-loading sports during growth must be recommended. In our study, bone asymmetry presented a weak correlation with the starting age of playing ($r > -0.3$ at the ultradistal radius). This result was possibly due to the small range in starting age of playing in the whole population (3.5–13.1 years, except one adult who started playing at 17.4 years). Some authors reported better correlations ($-0.48 < r < -0.56$, $P < 0.05$) in 19 females showing a wide range in starting age of playing (11–25 years) [34], whereas they found no correlation in 91 females showing a much smaller range (4–11 years) [28]. Interestingly, the young tennis players included in the present study displayed a relatively high correlation between their starting age of playing and the BMD asymmetry at the ultradistal radius ($r = -0.40$, $P < 0.05$). In female players, it has been convincingly demonstrated that the benefit of playing, in terms of bone mineral gain, was about two times greater if females started playing at or before menarche rather than after it [26].

This point is of critical importance regarding the prevention of fractures. Jones et al. [19] found that the girls who sustained a distal forearm fracture displayed a lower bone mass than the girls who did not, both at the time of the fracture and 4 years after the fracture had occurred. Low bone mass is considered as a major determinant of the fracture risk [35], even if bone strength does not solely rely on BMC or areal BMD [36]. Sum Siu et al. [37] showed that both areal BMD and bone geometry were closely related to bone strength. Knowing the distal forearm is the most common site of fractures in children [15–17], it seems relevant to promote mechanical loading at this site to improve bone mineralization.

The highest occurrence of fracture in children is close to the age at which the discordance between height gain and the accrual of volumetric BMD is most pronouced [16,38]. The peak of statural growth velocity precedes the peak of maximal bone mass gain, thereby inducing a transient fragility of the skeleton [39,40]. This delay seems to be more prominent in boys than in girls, probably because growth in height is more rapid in boys [41]. The results of the present study illustrate the capacity of tennis playing to improve bone mineralization at the distal radius before PHV. Consequently, children must be encouraged to practice impact-loading physical activity before attaining PHV to prevent fractures.

Furthermore, it has been suggested that starting to exercise during prepuberty [1] or more generally during the growing years [4,30] would magnify the changes in bone size associated with growth. Changes in bone geometry can be estimated by studying changes in bone area by DXA, interpreting the results with caution given the planar nature of this method [14,42,43]. At the mid-distal and third-distal radius in children, we found a very slight increase in BMD in comparison to the asymmetry in bone area. Mechanical strains during childhood and early adolescence were shown to induce preferentially a periosteal expansion (on the outer surface of cortical bone) [13,44]. As a consequence, the bone resistance to breaking and torsion is enhanced because the mineral mass is placed further from the long axis of the bone [8,45]. In addition to the role played by muscle contractions [46–50], this adaptation may be emphasized by the tennis-induced bending and torsion forces, which better promote periosteal expansion than compressive forces do [30].

We found a moderate asymmetry in bone area at the ultradistal radius in adult players (+5.4%). This result is consistent with previous studies showing a small cortical enlargement in response to tennis playing at long bone ends [8,10,44]. In our study, the young players displayed a small but significant asymmetry in bone area at the ultradistal radius (+4.9%, $P < 0.0001$), indicating that periosteal enlargement at ultradistal skeletal sites was effective but remained limited.

It has been suggested that an increased density of trabecular bone could be an alternative mechanism to build a stronger bone in the epiphyses [10]. In our group of young players, the side-to-side difference reached 16.3% in BMC and 10.6% in BMD at the ultradistal radius. This result suggests that trabecular bone may respond rapidly in children, even after a few years of tennis practice. The interaction between mechanical loading and natural skeletal growth may be emphasized at the ultradistal radius containing a high percentage of trabecular bone. Our findings are consistent with previous animal studies, which showed that growing trabecular bone is able to respond to mechanical loading [51,52], increasing its mineral mass through an increase in trabecular bone volume (BV/TV) and trabecular number [53].

The present study gave evidence that immature bone enduring longitudinal growth has the capacity to respond positively to mechanical loading. The total amount of time spent on tennis courts seems to be a strong determinant of the cortical bone response to tennis loading. The design of our study did not permit to determine whether there could exist an optimal pubertal stage to magnify bone response to loading. Nevertheless, our results should encourage children to practice physical activity before puberty or in early puberty. Changes in the external bone size and in the density of the trabecular bone can be observed in long bones in response to loading. These findings support the idea that exercise during growth is undoubtedly one of the best strategy to prevent fractures.

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