

Comparison of pQCT parameters between ulna and radius in retired elite gymnasts: the skeletal benefits associated with long-term gymnastics are bone- and site-specific

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Abstract

Objectives: To compare the skeletal benefits associated with gymnastics between ulna and radius. **Methods:** 19 retired artistic gymnasts, aged 18-36 years, were compared to 24 sedentary women. Bone mineral content (BMC), total and cortical bone area (ToA, CoA), trabecular and cortical volumetric density (TrD, CoD) and cortical thickness (CoTh) were measured by pQCT at the 4% and 66% forearm. **Results:** At the 4% site, BMC and ToA were more than twice greater at the radius than ulna whereas at the 66% site, BMC, ToA, CoA, CoTh and SSIpol were 20 to 51% greater at the ulna than radius in both groups ($p < 0.0001$). At the 4% site, the skeletal benefits in BMC of the retired gymnasts over the non-gymnasts were 1.9 times greater at the radius than ulna ($p < 0.001$), with enlarged bone size at the distal radius only. In contrast, the skeletal benefits at the 66% site were twice greater at the ulna than radius for BMC and CoA ($p < 0.01$). **Conclusion:** Whereas the skeletal benefits associated with long-term gymnastics were greater at the radius than ulna in the distal forearm, the reverse was found in the proximal forearm, suggesting both bones should be analysed when investigating forearm strength.

Keywords: peripheral Quantitative Computed Tomography, Bone Geometry, Volumetric Bone Density, Gymnastics, Forearm

Introduction

Since its introduction in the seventies^{1,2}, peripheral quantitative computed tomography (pQCT) has been increasingly used to investigate bone strength and its determinants, i.e. bone geometry and volumetric bone mineral density (BMD)^{3,4}. This technology offered new opportunities to investigate the effects of exercise on bone strength both in adults⁵⁻⁷ and children⁸⁻¹⁰.

Traditionally, pQCT investigations have been conducted at the forearm and lower leg. Forearm measurements have been

performed at different relative or absolute distances from the radial distal endplate^{3,4} and interestingly, bone geometry and volumetric BMD are reported at the radius only. Reference data for pQCT measurements at the forearm all refer to the radius, both in adults¹¹⁻¹⁴ and children¹⁵⁻¹⁸. Historically, pQCT measurements were performed at the radius because of its accessibility and vulnerability to fractures⁴. However, the analysis of the distribution of bone mass along the length of the radius and ulna (from their distal ends up to the mid-shaft) showed that radial bone mineral mass is almost constant from 1.5 cm proximal to the radial styloid tip to the olecranon¹⁹. In contrast, there is a progressive increase in ulnar bone mineral mass from about 4 cm proximal to the ulnar styloid tip up to the mid-shaft¹⁹. This mirrors the fact that cross-sectional bone size from the distal to the proximal forearm increases for the ulna and decreases for the radius. Depending on the muscles activated and the weight-bearing component of gymnastics maneuvers, bending or torsional forces are applied to radius and ulna. The ulna is likely to have a significant contribution to bending strength at the mid-forearm.

We recently showed that retired gymnasts displayed greater bone mass and size in the peripheral skeleton when compared to non-active age-matched women, even several years after re-

At the time of the study, Dr Prisca Eser worked as the Australian consultant for Stratec Medizintechnik, Pforzheim, Germany. All other authors have no conflict of interest.

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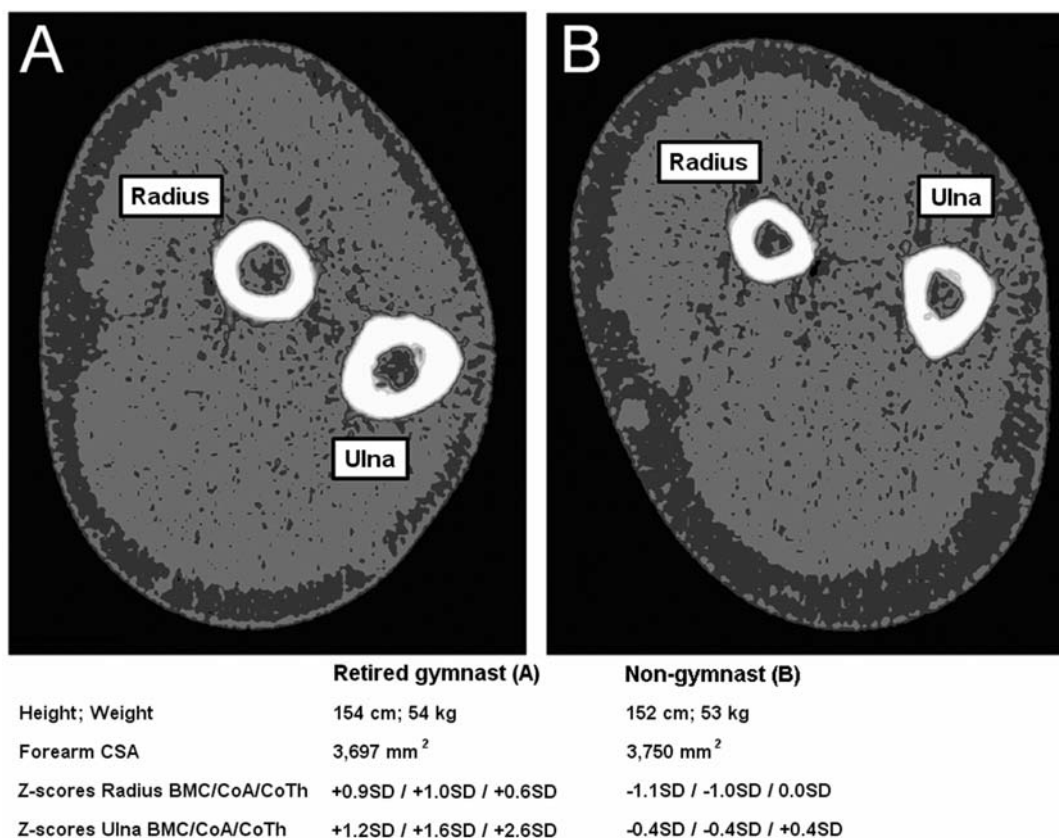


Figure 1. Examples of pQCT scans at the 66% forearm obtained in a retired gymnast (A) and a non-gymnast subject (B).

tirement²⁰. Retired gymnasts had 16-35% greater radial bone mass, size and strength than the non-gymnast subjects. Observation of the pQCT scans seemed to indicate that retired gymnasts also had greater bone mass, size and strength at the ulna.

The objectives of the study were: 1) to compare retired elite gymnasts and age-matched sedentary women in terms of pQCT-derived bone parameters at the radius and ulna; 2) to compare the magnitude of the skeletal benefits associated with long-term gymnastics between the radius and ulna. We hypothesized that: 1) the retired elite gymnasts would present with greater radial and ulnar bone parameters than the non-gymnast group, 2) investigating the radius only would underestimate the skeletal benefits associated with long-term gymnastics on overall forearm bone mass, size and strength.

*Footnotes: The retired gymnast was 22 years old, had menarche at the age of 18 years, and started gymnastics at the age of 9.2 years. She was selected because she trained for up to 35 hours a week at the peak of her career. She had been retired for 3 years at the time of the experiments. The non-gymnast was 44 years old and had menarche at the age of 10 years. She was selected to match subject (A) for height, weight and forearm cross-sectional area. BMC: Bone mineral content (g/cm); CoA: cortical area (mm²); CoTh: Cortical thickness (mm). Reference for Z-score calculation: non-gymnast group.

Materials and methods

Subjects

A total of 55 pre-menopausal female subjects were recruited for this study, consisting of 25 retired artistic gymnasts (age range: 17-36 years) and 30 age-matched non-gymnasts (age range 18-44 years). Inclusion criteria for the retired gymnasts were: 1) participation in high-level, competitive gymnastics during growth (childhood and adolescence) for at least four years, training for a minimum of fifteen hours per week at the peak of their career; 2) retirement from the sport for at least three years; and 3) participation in no more than two hours per week of regular physical activity since retirement. Inclusion criteria for the non-gymnasts were participation in no more than two hours per week of regular physical activity during growth and adulthood. Furthermore, both groups were required to have no history of disease known to affect bone health and no recent long-term periods of bed-rest or limb immobilisation.

Subjects were recruited through Gymnastics Australia, staff and students of Deakin University and word of mouth. The Deakin University Human Research Ethics Committee for the Faculty of Health, Medicine, Nursing and Behavioural Sciences approved the study, and written consent was obtained from all participants.

Medical questionnaire and history of training

Data on menstrual history and age at menarche were collected by questionnaire. Primary amenorrhoea was defined as the failure to menstruate by the age of 15 years²¹. Secondary amenorrhoea was defined as the absence of menses for 3 months or more after menarche²².

The questionnaire was also used to collect information on the use of contraceptives, fracture history, as well as past and present activity status. In gymnasts, further questions included: age at onset of gymnastics training, interruptions to their gymnastics career and age at retirement from gymnastics training. In addition, level of competition (e.g. national, international) and training volume (hours/week, including competitions) were reported for each year of training, from the beginning until the end of the career. The largest annual mean training volume was used for the statistical analysis and referred to as 'maximum training volume'.

Anthropometric measurements

Body weight was measured on a balance scale to the nearest 0.05 kg, in light clothing and without footwear. Standing height was measured using a stadiometer to the nearest 0.1 cm. Participants were asked about dominance of hand and consequently the limb to be measured was determined as the non-dominant arm (except if a fracture had occurred within the last 5 years, in which case the other limb was used).

Peripheral quantitative computed tomography (pQCT)

Bone parameters were measured at the forearm using peripheral quantitative computed tomography (Stratec XCT-3000 scanner, Stratec Medical, Pforzheim, Germany, Figure 1).

The scanner was positioned on the nondominant distal forearm. A coronal computed radiograph (scout view) was carried out. The scout view was used to position the reference line at the measurement site. At the radius, the reference line was perpendicular to scanning direction and was positioned on the lateral, most horizontal part of the radius distal endplate (automatic placement provided by the manufacturer).

Forearm length was measured from the tip of the olecranon process to the most distal end of the ulna styloid process using a metal measuring tape (precision: 0.5 cm). Forearm length was measured twice, with a third measurement if the first two results differed. Two pQCT scans were performed at 4% and 66% of the forearm length, proximal to the ulnar styloid process^{17,18}. Slice thickness was 2 mm, and voxel size was set at 0.5 mm with a scanning speed of 20 mm/s. Image processing and calculation of numerical values were performed using the manufacturer's software package (version 6, Stratec Medical, Pforzheim, Germany).

Epiphyses (4% distal forearm): the periosteal surface of the radius/ulna epiphysis was found by a contour algorithm based on thresholding at 180 mg/cm³. Bone mineral content (BMC, g per cm of slice thickness), total bone cross-sectional area (ToA, mm²) and total bone volumetric bone mineral density (ToD mg/cm³) were determined. Concentric pixel layers were then peeled off from the bone's perimeter until a central area covering 45 % of ToA was left. From this central area trabecular

volumetric bone mineral density (TrD, mg/cm³) was measured. Cortical thickness (CoTh, mm) at the distal ulna and radius was obtained using the method described by Rauch et al.²³. The Bone Strength Index (BSI, mg²/mm⁴) was calculated to estimate epiphyseal bone strength: $BSI = ToA * ToD^2$ ²⁴.

Diaphyses (66% forearm): the periosteal surfaces of the radial and ulnar diaphyses were found by a contour algorithm based on a threshold of 280 mg/cm³ and analysed separately. Bone mineral content (BMC, g/cm) and total bone cross-sectional area (ToA, mm²) were calculated. Cortical bone was selected by thresholding at 710 mg/cm³. Of the selected area, cortical cross-sectional area (CoA, mm²) and cortical bone mineral density (CoD, mg/cm³) were calculated. Cortical thickness (CoTh, mm) was calculated based on the assumption that all compartments of the bone shaft are cylindrical. To assess the influence of partial volume effect²⁵, CoD was linearly correlated with CoTh. Partial volume effect is when voxels at the bone edges are incompletely filled, which can lead to an underestimation of cortical density in cortices that are thinner than 2.5 mm²⁵⁻²⁷. Medullary cross-sectional area (MedA, mm²) was calculated by subtracting CoA from ToA. Polar strength strain index (SSI_{pol}), which is an estimate of bone's resistance to bending and torsion²⁸, was obtained using the manufacturer's software package.

Muscle cross-sectional area (muscle CSA, mm²) was obtained by subtracting fat CSA (mm²) and radial and ulnar ToA from the CSA of the forearm. Subcutaneous fat CSA was determined by selecting the area with thresholds -40 to +40 mg/cm³ hydroxyapatite density.

Precision errors for bone parameters were shown to be around 2% in adults²⁹. The effective dose for each scan including scout view was calculated to be 0.7 μSv (provided by the manufacturer).

Dual-energy x-ray absorptiometry (DXA)

Body composition at the whole body was determined by DXA (Prodigy, Lunar Corp, Madison, WI), with analysis software version enCORE Multimedia version 8.10.027. Positioning of patients was made according to standard procedures. The precision for this technique was determined in our lab at 2.9% for total fat mass and 1.6% for lean tissue mass.

Data analysis

Data were presented as mean ± standard error of the mean (SEM). The Gaussian distribution of the parameters was tested by the Kolmogorov–Smirnov test. Alpha level for statistical significance was set at 0.05. Baseline characteristics were compared between retired gymnasts and non-gymnasts using t-tests for independent samples. Bone parameters of the radius and ulna, as well as body composition, were compared between these two groups after adjustment for height using a one-way ANCOVA. Fisher's exact test was used to compare the incidence of fracture between the two groups. The effect size between the retired gymnasts and the non-gymnasts was evaluated using Z-scores. This allows comparing two groups with different distributions and parameters with different units. Individual Z-

	Retired Gymnasts (n=19)	Non-gymnasts (n=24)
Age (yrs)	22.5±1.1	25.3±1.3
Age at menarche (yrs)	14.7±0.5	12.2±0.2 ^a
Gynaecological age (yrs) ¹	7.9±1.1	13.1±1.4 ^b
Height (cm)	161.3±1.5	164.1±1.6
Weight (kg)	60.0±1.6	61.9±2.4
Forearm length (cm)	24.9±2.8	25.5±3.5
Lean body mass (kg)*	40.8±1.1	38.2±1.0
Forearm muscle CSA (mm ²)*	2911.6±78.2	2490.7±69.5 ^a
Percent body fat (%)*	28.6±1.4	31.1±1.3

¹Gynaecological age=chronological age – menarcheal age (years)
^ap<0.0001, ^bp<0.01: Differences between retired gymnasts and non-gymnasts
*Height-adjusted values, using ANCOVA

Table 1. Anthropometric data and body composition as measured by DXA in retired elite artistic gymnasts and age-matched non-gymnasts. History of training is given for the retired elite gymnasts (mean±SEM).

scores, expressed in standard deviations (SD), were calculated for the retired gymnasts using the following formula:

$$Z\text{-score} = \frac{\text{Subject's Result} - \text{Mean}_{\text{Non-gymnast group}}}{\text{Standard Deviation}_{\text{Non-gymnast group}}}$$

Significance of the Z-score was tested against zero using a one-sample t-test. The associations between variables were tested using the Pearson product moment correlation coefficient. All statistical procedures were performed with the software SPSS for Windows, version 17.0.1 (SPSS Inc., Chicago, Illinois, USA, 2008).

Results

Five of the retired gymnasts and two of the non-gymnasts had movement artifacts in their pQCT scans (either at the radius or at the ulna) and were therefore excluded from analysis. A 36-year-old gymnast was excluded from all analyses because she showed pQCT-derived bone parameters at the radius of 4.4 to 6.3 SD above the mean. Inclusion of this single observation resulted in a 20-38% increase in the mean Z-score for BMC at the forearm in the group of retired gymnasts. Four non-gymnasts reported secondary or primary amenorrhoea and were excluded from analysis because episodes of amenorrhoea were shown to affect pQCT outcomes³⁰ and the objective was to investigate the benefits of gymnastics training against a eumenorrhoeic non-gymnast group.

The final sample size included 19 retired elite artistic gymnasts and 24 non-gymnasts. Background variables for the participants are given in Table 1. The starting age of training in the group of retired gymnasts was 5.8±0.5 years, with a maximum training volume of 24.2±1.8 hours per week. The retired gymnasts' career lasted for 10.5±0.7 years and they had been retired for an average of 5.8±0.9 years at the time of the experiments. Nine of the gymnasts reported history of amenorrhoea (47%). More non-gymnasts than retired gymnasts (15 vs. 5) reported using oral contraceptive pill. The retired gymnasts re-

ported 8 fractures since puberty, versus 5 for non-gymnasts (difference not significant).

Comparison of the pQCT-derived bone parameters between retired gymnasts and non-gymnasts

Bone parameters obtained by pQCT in the two groups were indicated for the radius and ulna in Table 2. The differences between the retired gymnasts and non-gymnasts were given in Table 3, after adjusting for height. Adjustment for height was performed because differences in body size, although small and non-significant, could have influenced the between-group differences in bone parameters. All parameters were greater in the retired gymnasts than the non-gymnasts at the radius (except CoTh 4% and 66%, CoD and TrD) but also the ulna (except ToA 4%, CoTh 4% and CoD). Radial CoD was lower in the retired gymnasts than in the non-gymnasts. At the 66% site, ten out of 19 retired gymnasts and 8 out of 24 non-gymnasts had radial CoTh lower than 2 mm, whereas none of the subjects had ulnar CoTh lower than 2 mm. Only two participants (two non-gymnasts) had radial cortical thickness greater than 2.5 mm, whereas at the ulna 16 retired gymnasts and 16 non-gymnasts had cortical thickness greater than 2.5 mm. A significant correlation was found between CoTh and CoD in the whole sample at the radius ($r=0.68$, $p<0.0001$) and ulna ($r=0.34$, $p<0.05$). Forearm muscle CSA was strongly correlated with all bone parameters but TrD, CoD and CoTh (ulna: 0.43-0.69, radius: $r=0.46$ -0.75, $p<0.05$ -0.0001).

Comparison of the pQCT-derived bone parameters between radius and ulna

Table 2 presents the relative differences in bone parameters between the radius and ulna. At the 4% site, BMC and ToA were more than twice greater at the radius than the ulna in both groups ($p<0.0001$). The opposite was found at the 66% site, with BMC, ToA, CoA, CoTh and SSIpol being greater at the ulna than the radius in both groups ($p<0.0001$). In the shaft, ulnar parameters were 20-51% and 22-37% greater than radial parameters in the retired gymnasts and non-gymnasts, respectively.

At the 4% site, values of radial BMC and ToA represent approximately 70% of the corresponding values at the whole forearm (ulna + radius) whereas at the 66% site, radial BMC, ToA, CoA and CoTh represent only 41-46% of the corresponding values at the whole forearm in retired gymnasts (Table 2). Similar observations were made in non-gymnasts.

Magnitude of the skeletal benefits associated with long-term gymnastics: comparison between radius and ulna

Table 3 presents the between-group differences in bone parameters at the radius, ulna and radius+ulna. These differences were expressed in Z-scores to illustrate the skeletal benefits of training history in gymnastics. The magnitude and direction of the skeletal benefits associated with long-term gymnastics varied between epiphysis and diaphysis.

- Epiphysis (4% site)

At the 4% site, skeletal benefits (i.e. significant difference between retired gymnasts and non-gymnasts) were found for

	Ulna		Radius		% Differences Ulna vs. Radius ²	
	Mean±SEM	% Forearm ¹	Mean±SEM	% Forearm ¹	Mean difference	95% C.I.
Retired Gymnasts (n=19)						
4% site						
BMC (g/cm)	0.55±0.02	30	1.29±0.04	70	-57.2%**	(-58.9;-55.6)
ToA (cm ²)	163.5±4.9	29	410.1±18.0	71	-59.7%**	(-63.0;-56.4)
CoTh (mm)	0.44±0.04		0.74±0.03		-33.0%**	(-47.9;-18.2)
TrD (mg/cm ³)	226.2±8.3		202.4±8.2		+13.8%**	(7.1;20.5)
BSI (mg ² /mm ⁴)	19.4±1.3		41.9±2.0		-53.3%**	(-57.6;-49.0)
66% site						
BMC (g/cm)	1.63±0.04	59	1.11±0.03	41	+47.3%**	(37.8;56.8)
ToA (cm ²)	210.4±8.0	54	176.2±6.6	46	+19.5%**	(12.7;26.4)
CoA (mm ²)	118.6±3.2	60	79.4±2.2	40	+51.5%**	(38.8;64.3)
MedA (mm ²)	91.8±5.9	48	96.8±6.4	52	-4.3%	(-13.6;5.1)
CoD (mg/cm ³)	1134.1±9.0		1087.4±9.0		+4.3%**	(2.3;6.3)
CoTh (mm)	2.81±0.06		1.97±0.07		+45.8%**	(33.5;58.4)
SSIpol (mm ³)	506.1±24.0		346.0±13.7		+48.3%**	(30.3;66.3)
Non-gymnasts (n=24)						
4% site						
BMC (g/cm)	0.50±0.01	32	1.08±0.03	68	-53.3%**	(-55.7;-50.9)
ToA (cm ²)	162.7±4.4	33	327.1±8.1	67	-49.6%**	(-52.3;-46.9)
CoTh (mm)	0.44±0.03		0.81±0.04		-45.5%**	(-52.5;-38.6)
TrD (mg/cm ³)	198.8±7.3		182.4±6.4		+11.3%**	(4.3;18.4)
BSI (mg ² /mm ⁴)	15.6±0.9		35.7±1.6		-55.6%**	(-60.2;-50.9)
66% site						
BMC (g/cm)	1.28±0.04	57	0.98±0.02	43	+31.8%**	(26.2;37.3)
ToA (cm ²)	161.1±7.1	55	133.7±5.9	45	+22.4%**	(15.2;29.6)
CoA (mm ²)	94.5±2.9	57	72.0±1.9	43	+31.9%**	(25.7;38.1)
MedA (mm ²)	66.6±5.2	53	61.7±5.6	47	+15.5% [‡]	(1.5;29.5)
CoD (mg/cm ³)	1152.1±8.0		1137.8±8.0		+1.4%	(-0.3;3.0)
CoTh (mm)	2.58±0.06		2.14±0.06		+22.5%**	(14.6;30.3)
SSIpol (mm ³)	348.2±21.4		258.1±12.1		+36.5%**	(26.1;46.8)
<p>Values are given as mean ± standard error of the mean (SEM). BMC: bone mineral content; ToA: total cross-sectional area; CoA: cortical cross-sectional area; MedA: medullary cross-sectional area; TrD: trabecular volumetric bone mineral density; CoD: cortical volumetric bone mineral density; CoTh: cortical thickness; BSI: bone strength index; SSIpol: strength strain index.</p> <p>¹Values in each bone (ulna and radius) are also expressed as a percentage of the values in forearm bones, i.e. ulna + radius ('% Forearm'). For the ulna: Value Ulna * 100/Value Ulna+Radius For the radius: Value Radius * 100/Value Ulna+Radius</p> <p>Masses and areas are additive, but characteristics such as densities and thicknesses are not. Therefore % Forearm values were not calculated for CoD, TrD, CoTh, BSI and SSIpol</p> <p>²The relative differences in bone parameters between the ulna and radius are indicated, with 95% confidence intervals. % Difference Ulna vs. Radius: (Value Ulna-Value Radius)/Value Radius *100 Ulna ≠ Radius: [‡]p<0.05; ^{**}p<0.001</p> <p>For all parameters but ulnar CoD (66% site), ulnar ToA and CoTh (4% site), radial CoTh (4% and 66% sites) and radial TrD (4% site): differences between retired gymnasts and non-gymnasts, p<0.05-0.0001.</p>						

Table 2. Comparison of the ulna vs. radius for peripheral quantitative computed tomography-derived bone parameters at the 4% and 66% sites in retired elite gymnasts and non-gymnasts.

BMC and BSI in both bones (Z-scores +0.8 to +1.5 SD, p<0.01). The skeletal benefits in the retired gymnasts were 1.9 times greater at the radius than the ulna for BMC (p<0.001). Long-term gymnastics loading was also associated with a larger bone size at the distal radius but not the distal ulna (ToA +2.1 SD vs. +0.04 SD, at the radius and ulna respectively, p<0.001).

- Diaphysis (66% site)

At the 66% radius, skeletal benefits were found for BMC, ToA, CoA, MedA and SSIpol (Z-scores +0.7 to +1.3 SD, p<0.01). In contrast to the 4% site, the 66% ulna showed greater benefits than the 66% radius: BMC (+1.6 SD, 1.8 times greater benefits), CoA (+1.5 SD, 2.2 times greater benefits)

	Ulna			Radius			Ulna+Radius ¹		
	Mean difference	95% C.I.	Z-scores	Mean difference	95% C.I.	Z-scores	Mean difference	95% C.I.	Z-scores
4% site									
BMC (g/cm)	+0.06 ^b	(0.01;0.10)	+0.8 SD ^{‡‡}	+0.24 ^d	(0.16;0.33)	+1.5 SD	+0.30 ^d	(0.18;0.42)	+1.4 SD
ToA (cm ²)	+0.8	(-12.7;14.3)	+0.04 SD ^{‡‡}	+94.2 ^d	(60.0;128.4)	+2.1 SD	+95.0 ^d	(54.8;135.1)	+1.3 SD
CoTh (mm)	0.00	(-0.1;0.1)	+0.04 SD [‡]	-0.08	(-0.18;0.03)	-0.4 SD			
TrD (mg/cm ³)	+26.4 ^a	(3.6;49.2)	+0.8 SD	+20.3	(-1.1;41.7)	+0.7 SD			
BSI (mg ² /mm ⁴)	+3.6 ^a	(0.5;6.8)	+0.9 SD	+6.7 ^a	(1.6;11.9)	+0.8 SD			
66% site									
BMC (g/cm)	+0.38 ^d	(0.26;0.50)	+1.6 SD [‡]	+0.16 ^d	(0.09;0.23)	+0.9 SD	+0.54 ^d	(0.37;0.71)	+1.4 SD [‡]
ToA (cm ²)	+55.6 ^d	(33.9;77.3)	+1.4 SD	+47.7 ^d	(29.7;65.7)	+1.2 SD	+103.3 ^d	(66.2;140.4)	+1.4 SD
CoA (mm ²)	+26.6 ^d	(17.8;35.4)	+1.5 SD [‡]	+9.4 ^b	(3.5;15.3)	+0.7 SD	+36.0 ^d	(23.8;48.3)	+1.3 SD [‡]
MedA (mm ²)	+29.0 ^c	(12.9;45.1)	+1.1 SD	+38.3 ^d	(21.0;55.6)	+1.3 SD	+67.3 ^d	(36.6;98.0)	+1.3 SD
CoD (mg/cm ³)	-19.5	(-44.1;5.2)	-0.6 SD	-54.0 ^d	(-78.5;-29.5)	-1.2 SD			
CoTh (mm)	+0.24 ^b	(0.07;0.41)	+1.0 SD ^{‡‡}	-1.15	(-0.35;0.04)	-0.6 SD			
SSIpol (mm ³)	+170.6 ^d	(105.0;236.2)	+1.6 SD	+99.3 ^d	(62.0;136.5)	+1.2 SD			
<p>The between-group differences are expressed in two forms: the mean difference with the 95% confidence interval (adjusted for height), and Z-scores. Positive values of the Z-scores indicate Retired Gymnasts > Non-gymnasts. Reference for Z-score calculation: non-gymnast group. BMC: bone mineral content; ToA: total cross-sectional area; CoA: cortical cross-sectional area; MedA: medullary cross-sectional area; TrD: trabecular volumetric bone mineral density; CoD: cortical volumetric bone mineral density; CoTh: cortical thickness; BSI: bone strength index; SSIpol: strength strain index.</p> <p>¹Masses and areas are additive, but characteristics such as densities and thicknesses are not. Therefore CoD, TrD, CoTh, BSI and SSIpol were not calculated for Ulna + Radius.</p> <p>The differences between retired gymnasts and non-gymnasts are indicated in the 'Mean difference' column: ^ap<0.05, ^bp<0.01, ^cp<0.001, ^dp<0.0001 (this also indicates that Z-scores were significantly different from 0).</p> <p>Ulna ≠ Radius: [‡]p<0.05; ^{‡‡}p<0.001; Ulna+Radius ≠ Radius: ≠ p<0.05.</p>									

Table 3. Height-adjusted differences between retired gymnasts (n=19) and non-gymnasts (n=24) for peripheral quantitative computed tomography-derived bone parameters at the radius, ulna and ulna+radius.

and CoTh (+1.0 SD, 3.7 times greater benefits) (p<0.01). At the 66% forearm, analysing the radius only, rather than radius and ulna together, lead to an underestimation of the skeletal benefits in retired gymnasts for the following parameters: BMC (+0.9 SD vs. +1.4 SD, 55% underestimation) and CoA (+0.7 SD vs. +1.3 SD, 85% underestimation). The skeletal benefits were also greater for ToA (+12%) but this did not reach significance. While retired gymnasts tended to have thinner cortices at the 66% radius (-0.6 SD, ns), they had thicker cortices at the 66% ulna (+1.0 SD, p<0.01).

Discussion

The study showed that long-term gymnastics training was associated with marked skeletal benefits not only at the radius but also at the ulna. At the distal forearm, the skeletal benefits were greater at the radius than the ulna, probably due to the fact that the distal radius is more than twice bigger than the distal ulna and bears most of the load. Contrasting findings were obtained in the proximal forearm, where the ulna is 20% bigger: the retired gymnasts had approximately twice greater skeletal benefits at the ulna than the radius for bone mineral content and cortical cross-sectional area.

Our observations are in accordance with several studies

which showed positive effects of exercise on ulnar bone strength and its determinants. Investigations in tennis and squash players using conventional radiographs and DXA showed that the ulna has greater bone size³¹, bone mineral content and areal BMD^{32,33} in the playing arm compared to the nonplaying arm. Ulnar bending stiffness, as measured by mechanical response tissue analyser (low frequency vibration stimulus), was found to be greater in female swimmers and gymnasts³⁴, and also active men³⁵, when compared to sedentary subjects. Unilateral isokinetic training was shown to increase ulnar bending stiffness in young women³⁶.

The findings also support recent pQCT investigations on upper limb bone strength in cricketers, swimmers and controls³⁷. Rather than reporting bone strength at the radius, the authors investigated ulnar bone strength and shape. They found greater side-to-side differences in bone strength (+16%) between the dominant and nondominant arms in cricketers compared to controls (+8%) (p<0.05). Previous pQCT studies on the skeletal benefits of gymnastics investigated the radius, but not the ulna^{9,38-40}.

Nevertheless, the fact that retired gymnasts showed greater skeletal benefits at the ulna 66% than the radius 66% was in contradiction with previous findings in tennis and squash players. Racket sports studies showed that the ulna was less responsive to repetitive loading (side-to-side differences in BMC and BMD

+3-8%) than the radius (+6-15%) or the humerus (+15-28%)^{32,33}. In these studies, BMC and BMD were measured at the mid shaft (around 50% of ulnar length) whereas we investigated bone geometry and volumetric BMD at 66% of ulnar length.

Although this difference might explain some of the discrepancies between findings, it could also be argued that tennis playing and gymnastics may have different loading modalities on the forearm, thereby inducing different bone adaptations. A unique aspect of gymnastics is the regular use of the upper extremities to support body weight⁴¹. The wrist is subjected to peak ground reaction forces ranging from 1.5 up to 3.6 times body weight in manoeuvres such as pommel horse exercises, round-off, back handspring and forward handspring⁴²⁻⁴⁴. Maximum loading rates up to 10 times body weight per second have been reported⁴⁴, which contributes to explain why the upper extremity is frequently injured in gymnasts⁴⁵. It is a competitive requirement to try to maintain straight arms during the double-arm support phase, this prohibits elbow flexion which would attenuate forces by increasing contact time⁴³. Internal forces acting on the radius and ulna include the measured ground reaction forces and arm muscle forces used to initiate and control the movement. Ground reaction forces are normally mostly taken up by the distal radius^{41,46} and are partly diverted to the ulna by the membrana interossea brachii^{47,48}. The fact that the distal radius seemed more responsive to loading than the distal ulna could be explained by the fact that it bears most of the load due its much larger cross-sectional area and its direct contact with carpal bones. Interestingly, injuries to the distal growth plate of the radius are common in pre-pubertal gymnasts^{41,49-53}. These injuries may lead to stunted growth of the radius and positive ulnar variance (ulna longer than radius at the distal end)^{41,46,51}, which in turn may accentuate the force transfer to the ulna during gymnastics manoeuvres. It was recently shown that subcortical aBMD at the distal radius was greater in subjects with negative ulnar variance, suggesting an indirect shift of axial forces through the ulna to the radius⁵⁴. Whether or not the reverse could be true with positive ulnar variance remains to be investigated.

The retired gymnasts displayed lower cortical density at the radius. However, a large majority of subjects had a cortical thickness lower than 2.5 millimetres in the radial shaft, which would have affected the accuracy of the results due to partial volume effect. Cortical density as assessed by pQCT increases with increasing cortical thickness^{26,27}, as confirmed by the positive association we found between cortical density and cortical thickness. At the ulna cortical density tended to be lower in the retired gymnasts but this difference was not significant. As cortical thickness was greater in the ulna than the radius at the 66% site, values of the ulna are less affected by partial volume effect and are therefore more reliable. A marked increase in total bone area at the expense of cortical density has been reported in the tibial diaphysis of jumpers⁵⁵. The tibia is less affected by partial volume effect than the radius. This suggests that the exercise-induced enlargement of the bone shaft may be achieved at the expense of cortical density.

This study presents several limitations. The findings are spe-

cific to the 4% and 66% forearm, and were obtained in a small sample. The response to loading was shown to be highly variable along the length of long bones, both in animals⁵⁶ and humans⁶. Therefore we cannot generalise our findings to any other sites at the forearm. Due to the cross-sectional nature of the investigations, the possibility of a selection bias in the group of retired gymnasts cannot be ruled out. However, it seems unrealistic to solely attribute the skeletal benefits in retired gymnasts to genetic factors because previous longitudinal studies have reported marked skeletal benefits in response to gymnastics training^{57,58}. Potential inaccuracies regarding menarcheal age and history of gymnastics training/physical activity must be acknowledged as this was a retrospective study³⁰. Although factors such as menarcheal age, history of amenorrhoea and oral contraceptive use differed between groups, the influence of these factors were not investigated in the present manuscript. Their influence on the skeletal benefits associated with long-term gymnastics has been discussed previously^{20,30}. Exposure to estrogen, which is thought to affect cortical and trabecular bone differently, was unlikely to explain the discrepancies in skeletal adaptations between radius and ulna because both bones have similar proportions of cortical and trabecular bone at a given distance from their distal end¹⁹. The retired gymnasts tended to report more fractures than the non-gymnasts. However, the type (e.g. stress fracture) and cause of fracture (low vs. high-trauma) were not sought in the questionnaire, therefore interpretation of these findings was difficult. Finally, most participants showed various amount of subcortical bone at the ulna and/or radius. Subcortical bone has a density lower than 710 mg/mm³ and as a result it was not included in the cortical area. Although this feature was not exclusive to the retired gymnasts and to the ulna, it may have affected the skeletal benefits found in the retired gymnasts in both bones.

Gymnastics is recognised as one of the most osteogenic sports, inducing high loads on both the upper and the lower body. At the forearm, the skeletal benefits associated with long-term gymnastics are bone- and site-specific. These benefits may be underestimated when analysing the radius only - which is common practice with the pQCT - rather than radius and ulna, particularly at the 66% site where the ulna is larger than the radius. Future investigations on the osteogenic effects of upper body exercise on forearm bone strength should require analysing both ulna and radius.

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