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Original Article

Skeletal differences at the ulna and radius between pre-pubertal non-elite female gymnasts and non-gymnasts

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Abstract

Objective: To compare skeletal parameters between the ulna and radius in pre-pubertal non-elite gymnasts and non-gymnasts. **Methods:** Fifty-eight non-elite artistic gymnasts, aged 6-11 years, were compared with 28 non-gymnasts for bone mineral content (BMC), total and cortical bone area (ToA, CoA), trabecular and cortical volumetric density (TrD, CoD) and estimated bone strength (BSI and SSIp), obtained by pQCT at the distal and proximal forearm. **Results:** Gymnasts had greater estimated bone strength than non-gymnasts at both sites of the forearm. At the distal forearm, the gymnastics-induced skeletal benefits were greater at the radius than ulna (Z-scores for BMC, TrD and BSI +0.40 to +0.61 SD, $p<0.05$ vs. +0.15 to +0.48 SD, NS). At the proximal forearm, the skeletal benefits were greater at the ulna than the radius (Z-scores for BMC, ToA, CoA and SSIp +0.59 to +0.82 SD, $p<0.01$ vs. +0.35 (ToA) and +0.43 SD (SSIp), $p<0.01$). **Conclusion:** Skeletal benefits at the distal and proximal forearm emerged in young non-elite gymnasts. Benefits were larger when considering skeletal parameters at both the ulna and radius, than the radius alone as traditionally performed with pQCT. These findings suggest the ulna is worth investigating in future studies aiming to accurately quantify exercise-induced skeletal adaptations.

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

Introduction

Gymnastics participation provides a unique model for assessing skeletal adaptations due to high impact loading and muscle strength requirements, particularly in the upper limbs. Elite gymnastics participation prior to puberty is associated with increased bone strength at the radius as measured by peripheral quantitative computed tomography (pQCT)[1]. Skeletal benefits appear to be maintained among elite gymnasts after retirement[2].

Previous investigations using pQCT on the upper limbs of pre-and early pubertal gymnasts[1,3,4] as well as retired or ex-gymnasts[2,4,5] have focused on the radius alone. Interestingly, although the radius is more than two times bigger, stronger and has more bone mass than the ulna at the distal forearm, the ulna has almost twice as much bone mass, cortical area and strength than the radius at the shaft, as demonstrated in former elite gymnasts and age-matched non-gymnasts[6]. Skeletal benefits associated with approximately ten years of high-level gymnastics participation were shown to be greater at the radius than the ulna at the distal forearm (4% site) whereas the opposite was found at the proximal forearm (66% site)[6]. Therefore, it is quite plausible that any future analysis of the radius without the inclusion of the ulna may result in error associated with estimating the skeletal benefits associated with gymnastics participation. These results are not limited to the upper extremities. Previous research on the lower extremities also showed discrepancies between bones in the same segment (i.e. tibia and fibula) when comparing groups of various ages[7] and loading exposure[8].

More recently, skeletal benefits induced by recreational gymnastics participation have been explored since this mode of exercise is a more realistic approach to promote children's bone health than high-intensity elite gymnastics. Pre-pubertal gymnasts and ex-gymnasts, who have previously completed 1.5 hr/wk of gymnastic training over a two year period, dis-

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played greater volumetric bone mineral density, bone mass and bone strength at the distal radius than controls[4]. No differences in bone size were evident for the radius between these gymnasts and controls[4]. However, skeletal differences between pre-pubertal non-elite gymnasts and non-gymnasts remain unexplored at the ulna. Therefore, similarly to what was found in retired elite gymnasts, assessing the radius alone may have underestimated skeletal benefits among pre-pubertal gymnasts.

The primary purpose of this study was to investigate pQCT-derived bone parameters at the distal and proximal radius and ulna in a group of pre-pubertal non-elite gymnasts and age-matched non-gymnasts. We hypothesize that gymnasts will display greater bone properties at the radius and the ulna compared with non-gymnasts.

Materials and Methods

A total of 86 pre-pubertal girls aged 6 to11 years were recruited for this study. Gymnasts were training between 1 and 16 hr/wk and had trained for at least six months in the sport. All gymnasts were recruited from local gymnastics facilities and were participating at a recreational or non-elite level, rather than participating at an elite level. Elite gymnasts are those competing at or aiming to compete at an international level. These gymnasts often train in excess of 25 hours per week, up to six days a week for 12 months of the year[9]. Non-elite gymnasts have lower weekly training commitments, and are not aiming for international competition.

Non-gymnasts were recruited via the ‘bring a friend’ recruitment strategy as well as referral. Non-gymnasts were involved in equal to or less than 4 hr/wk of organised physical activity outside school. All participants were healthy pre-pubertal girls, not taking any medication known to affect bone or muscle metabolism, and without fracture to the upper limb within the previous 12 months. The study was approved by the University’s ethics committees. Parental consent and child assent was obtained for all participants.

Anthropometric Assessment

A stadiometer (SECA height rod model 220, Hamburg, Germany) with an accuracy of 0.01 cm was used to measure standing height. Mass was recorded using digital scales (A&D Company Ltd., Tokyo, Japan) with an accuracy of 0.05 kg. Participants were asked about hand dominance and consequently the limb to be measured was determined as the non-dominant arm (except if a fracture had occurred, in which case the other limb was used). Forearm length was measured from the olecranon process to the ulnar styloid process using a metal measuring tape with an accuracy of 0.01 cm.

Body Composition

Body composition (lean and fat mass) was measured by dual-energy X-ray absorptiometry (DXA, Norland, XR-36 System, Fort Atkinson, Wisconsin). Measurements were performed at the predetermined scan mode (speed 180 mm/s, resolution 6.5x13.0 mm, source collimation 1.68 mm) with analysis software provided by the manufacturer (2.5.3a). Coefficients of variation in our laboratory were 1.3% for lean mass and 3.5% for fat mass.

Bone Mineral Density, Bone Geometry and Bone Strength

Bone parameters of the non-dominant forearm were measured by peripheral quantitative computed tomography (pQCT) (XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Given participants had an open growth plate at the distal radius, the reference line was positioned at the most distal portion of the growth plate, according to standard procedures[10,11]. Two tomographic slices of 2.3 mm thickness were obtained at the 4% and 66% ulna and radius sites measured distally, with 0.4 mm planar resolution and scan speed of 15 mm/s. Image processing and the calculation of bone parameters were conducted using the manufacturer’s software package (version 6.00). The coefficients of variation in our laboratory ranged from 0.7 to 1.4% for pQCT-derived bone parameters at the forearm. All bone analyses were conducted by the same technician and quality assurance checks of the pQCT device were regularly performed.

At the 4% distal site, bone mineral content (BMC), total bone area (ToA), trabecular density (TrD) and bone strength index (BSI) were determined for both the ulna and radius. Cortical thickness was obtained using the method described by[12]. The BSI was calculated as an assessment of bone strength and was determined using the following formula: BSI= the square of the total density (ToD) and the total cross-sectional area (ToA)[13]. At this site, variables were calculated using contour and peel mode 1 with a threshold of 180 mg/cm^3.

At the 66% site, BMC, ToA, cortical area (CoA), medullary area (MedA), cortical density (CoD), cortical thickness (CoTh), and the polar strength strain index (SSIp) were calculated. Cort mode 1 with a threshold of 711 mg/cm^3 was used for cortical bone and 280 mg/cm^3 for SSIp and ToA calculations.

Cortical thickness was calculated based on the assumption that all compartments of the bone shaft are cylindrical. Medullary area was calculated by subtracting CoA from ToA. Bone strength (SSIp) was obtained using the manufacturer’s software package.

Pubertal Stage

Maturation was assessed using a proxy report of Tanner’s five stage model for pubertal maturation[14]. Parents and daughters were asked to complete this questionnaire together. Participants with a combined Tanner score (breast + pubic hair) of three or less were included in this study.

Data Analysis

Data were presented as mean ± standard deviation (SD). 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 non-elite 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

	Non-Elite Gymnasts (n=58)	Non-Gymnasts (n=28)
Age (yrs)	8.6±1.3	8.5±1.3
Tanner stage 1 breast (n=, %)	51 (88%)	23 (82%)
Tanner stage 1 pubic hair (n=, %)	57 (98%)	28 (100%)
Height (cm)	134.6±6.6	135.9±6.8
Weight (kg)	30.1±5.6	32.1±6.2
Forearm length (cm)	19.0±1.6	19.0±1.4
Lean body mass (kg)	19.48±3.3	18.98±3.3
Fat body mass (kg)	9.11±3.0[b]	11.63±4.5
Gymnastics training hours (hr/wk)	6.9±4.7[a]	-
Total physical activity (hr/wk)	8.5±4.6[a]	2.0±1.4

[a]p<0.0001, [b]p<0.05: Differences between gymnasts and non-gymnasts

Table 1. Anthropometric data and bone mineral density as measured by DXA in non-elite artistic gymnasts and age-matched non-gymnasts (mean±SD).

after adjustment for body weight 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 non-elite 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-scores, expressed in standard deviations (SD), were calculated for the non-elite gymnasts using the following formula:

$$\text{Z-score}=(\text{Gymnast's Result}-\text{Mean}_{\text{Non-gymnast group}})/\text{Standard Deviation}_{\text{Non-gymnast group}}$$

Significance of the Z-score was tested against zero using a one-sample t-test. All statistical procedures were performed with the software SPSS for Windows, version 18 (SPSS Inc., Chicago, Illinois, USA).

Results

The pQCT scans of one gymnast (distal site) and three non-gymnasts (one distal and two proximal sites) were removed due to movement artifacts. In addition, four pQCT scans (two gymnasts and two non-gymnasts) were excluded at the distal site as radial TrD scores were higher than 320 mg/cm^3. Such values for TrD suggest scans were conducted too close to the growth plate, considering the 95th percentile for TrD is 260 mg/cm^3, based on reference data[11].

Descriptive variables are shown in Table 1. The gymnasts had an average training history of 2.8 years (range 0.5-6.0) and typically trained 7 hr/wk (range: 1 to 16 hr/wk). Non-gymnasts participated in 2 hr/wk of organised physical activity (range: 0 to 4 hr/wk). Organised physical activities among non-gymnasts included dancing, netball, soccer and swimming. Reports of previous fracture (>12 months prior) were not different between groups. Ten gymnasts had previously broken a bone compared with three non-gymnasts. Two fractures resulted from involvement in organised physical activity, one from gymnastics participation.

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

Bone parameters obtained by pQCT in the two groups are shown for the radius and ulna in Table 2. The differences between the gymnasts and non-gymnasts are provided in Table 3, after adjusting for body weight. Adjustment for body weight was deemed necessary, despite the absence of statistical differences between groups, because gymnasts were 6% lighter than non-gymnasts. With the exception of ToA at the distal radius, the remaining distal radial parameters were greater for gymnasts than non-gymnasts. In comparison, no differences were found between groups at the distal ulna. At the proximal forearm, groups were not different for CoD or radial BMC, CoA and CoTh. The remaining parameters were greater for gymnasts than non-gymnasts. Skeletal benefits at the distal radius were characterized by greater trabecular volumetric BMD without differences in bone geometry. However, the proximal forearm (radius and ulna) showed greater total cross-sectional bone size.

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

Table 2 shows the relative differences in bone parameters between the radius and ulna. At the distal site, BMC, ToA and BSI were more than twofold greater at the radius than the ulna in both groups (p<0.0001). The opposite was found at the proximal site, with BMC, ToA, CoA, MedA, and SSIp being greater at the ulna than the radius in both groups (p<0.0001). At the proximal forearm, bone parameters (with the exception of CoD and CoTh in the non-gymnasts) were 20% to 43% and 16% to 33% greater at the ulna than the radius in gymnasts and non-gymnasts, respectively.

The respective contribution of the radius and ulna to the overall bone mass and size of the distal and proximal forearm (ulna+radius) varies with location. At the distal site, values of radial BMC and ToA represent approximately 70% of the corresponding values at the whole forearm whereas at the proximal site, radial

	Ulna		Radius		% Differences (Ulna vs. Radius[2])	
	Mean±SD	**% Forearm[1]**	**Mean±SD**	**% Forearm[1]**	**Mean difference**	**95% C.I.**
Non-Elite Gymnasts						
4% site (n=55)						
BMC (g/cm)	0.33±0.10	32	0.71±0.18	68	-51.9%‡‡	(-57.1; -46.8)
ToA (cm^2)	103.2±16.6	30	236.5±49.0	70	-55.8%‡‡	(-57.1; -54.5)
TrD (mg/cm^3)	272.8±37.8		229.3±39.1		+20.1%‡‡	(16.0; 24.2)
BSI (mg2/mm4)	9.5±2.1		21.3±6.6		-54.0%‡‡	(-56.3; -51.7)
66% site (n=58)						
BMC (g/cm)	0.78±0.12	56	0.61±0.10	44	+30.2%‡‡	(26.7; 33.8)
ToA (cm^2)	119.7±22.1	56	95.7±17.8	44	+26.1%‡‡	(22.0; 30.2)
CoA (mm^2)	58.8±9.4	57	44±8.0	43	+32.5%‡‡	(27.8; 37.3)
MedA (mm^2)	60.9±17.5	54	51.7±16.3	46	21.7%‡‡	(14.4; 29.1)
CoD (mg/cm^3)	1012.4±43.7	1023.7±44.1			-1.1%‡	(-2.0; -0.3)
CoTh (mm)	1.79±0.26	1.51±0.26			+19.5%‡‡	(14.9; 24.0)
SSIp (mm^3)	189.8±48.8	135.0±32.4			+43.2%‡‡	(35.9; 50.6)
Non-Gymnasts						
4% site (n=25)						
BMC (g/cm)	0.30±0.06	31	0.66±0.13	69	-53.1%‡‡	(-56.8; -49.5)
ToA (cm^2)	109.2±20.0	31	241.2±46.6	69	-54.2%‡‡	(-57.0; -51.4)
TrD (mg/cm^3)	266.2±44.0		211.9±32.5		+24.3%‡‡	(17.8; 30.9)
BSI ($mg2/mm^4$)	8.8±2.4		18.3±4.9		-51.0%‡‡	(-55.6; -46.4)
66% site (n=26)						
BMC (g/cm)	0.71±0.11	54	0.61±0.09	46	+20.0%‡‡	(15.1; 24.9)
ToA (cm^2)	109.6±17.2	55	90.8±14.0	45	+21.16%‡‡	(16.4; 26.0)
CoA (mm^2)	50.6±10.7	54	43.9±9.0	46	+16.04%‡‡	(10.3; 21.8)
MedA (mm^2)	59.0±18.8	56	46.9±15.0	44	+28.7%‡‡	(17.6; 39.7)
CoD (mg/cm^3)	1028.3±59.6		1041.8±51.5		-1.3%‡	(-2.5; -0.1)
CoTh (mm)	1.60±0.38		1.54±0.35		+5.1%	(-1.2; 11.4)
SSIp (mm^3)	163.1±32.4		123.8±25.9		+33.3%‡‡	(25.9; 40.7)

Values are given as mean ± standard deviation of the mean (SD). 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; SSIp: polar strength strain index.

*[1]Values 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. 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 SSIp.*

*[2]The 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: ‡$p<0.05$; ‡‡$p<0.001$.

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

BMC, ToA, CoA and CoTh represent only 43% to 46% of the corresponding values at the whole forearm in gymnasts (Table 2). Similar observations were made in non-gymnasts.

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

Table 3 presents the between-group differences in bone parameters at the radius, ulna and radius+ulna. Differences are expressed in Z-scores to illustrate the skeletal benefits of training in non-elite artistic gymnastics. The magnitude and direction of the skeletal benefits associated with short-term non-elite gymnastics participation varied between the proximal and distal sites of the radius and ulna.

Distal (4% site)

At the distal radius, skeletal benefits (i.e. significant difference between gymnasts and non-gymnasts) were found for BMC, TrD and BSI (Z-scores +0.40 to +0.65 SD, $p<0.05$). Percent difference between gymnasts and non-gymnasts ranged from +8% to +16% at the distal radius. No differences were found between gymnasts and non-gymnasts at the distal ulna.

	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)	+0.03	(-0.02; 0.07)	+0.48 SD	+0.08[a]	(0.00; 0.15)	+0.40 SD	+0.11[a]	(0.02; 0.21)	+0.57 SD
ToA (cm^2)	-3.12	(-10.37; 4.14)	-0.30 SD‡	+3.95	(-15.15; 23.04)	-0.10 SD	+0.83	(-23.70; 25.36)	-0.17 SD‡
TrD (mg/cm^3)	+4.63	(-13.77; 23.03)	+0.15 SD‡‡	+18.99[a]	(1.26; 36.72)	+0.53 SD			
BSI (mg^2/mm^4)	+0.91	(-0.12; 1.94)	+0.30 SD	+3.66[a]	(0.83; 6.49)	+0.61 SD			
66% site									
BMC (g/cm)	+0.10[d]	(0.05; 0.14)	+0.65 SD‡‡	+0.02	(-0.01; 0.06)	-0.05 SD	+0.14[d]	(0.07; 0.22)	+0.49 SD‡‡
ToA (cm^2)	+14.04[c]	(6.15; 21.94)	+0.59 SD‡	+8.80[b]	(3.09; 14.51)	+0.35 SD	+22.84d	(10.47; 35.20)	+0.51SD‡
CoA (mm^2)	+10.05[d]	(6.26; 13.84)	+0.77 SD‡‡	+2.46	(-0.77; 5.70)	+0.09 SD	+12.36[d]	(6.01; 18.70)	+0.47 SD‡‡
MedA (mm^2)	+3.99	(-3.86; 11.85)	+0.10 SD	+7.23[a]	(0.56; 13.90)	+0.33 SD	+11.22	(-1.95; 24.39)	+0.21 SD
CoD (mg/cm^3)	-12.86	(-35.47; 9.75)	-0.27 SD	-15.60	(-37.18; 5.98)	-0.35 SD			
CoTh (mm)	+0.21[b]	(0.07; 0.34)	+0.49 SD‡‡	-0.01	(-0.15; 0.12)	-0.09 SD			
SSIp (mm^3)	+35.64[d]	(19.15; 52.13)	+0.82 SD‡	+18.46[d]	(8.46; 28.47)	+0.43 SD			

The between-group differences are expressed in two forms: the mean difference with the 95% confidence interval (adjusted for body weight), and Z-scores (not adjusted for body weight). Positive values of the Z-scores indicate Non-elite 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; SSIp: polar strength strain index.

[1]Masses and areas are additive, but characteristics such as densities and thicknesses are not. Therefore CoD, TrD, CoTh, BSI and SSIp were not calculated for Ulna + Radius. The differences between non-elite gymnasts and non-gymnasts are indicated in the 'Mean difference' column: [a]$p<0.05$, [b]$p<0.01$, [c]$p< 0.001$, [d]$p<0.0001$ (this also indicates that Z-scores were significantly different from 0). ≠Radius: ‡$p<0.05$; ‡‡$p<0.001$.

Table 3. Body weight-adjusted differences between non-elite artistic gymnasts and non-gymnasts for peripheral quantitative computed tomography-derived bone parameters at the radius, ulna and ulna+radius.

Proximal (66% site)

At the proximal radius, skeletal benefits were found for ToA and SSIp (Z-scores +0.35 to +0.43 SD, p<0.05). In contrast to the distal site, the proximal ulna showed greater benefits than the proximal radius: SSIp (+0.82 SD), CoA (+0.77 SD), BMC (+0.65 SD), ToA (+0.59 SD) and CoTh (+0.49 SD), (p<0.01). Benefits at the proximal radius and ulna ranged from +5% to +16% for the gymnasts compared with non-gymnasts. At the proximal forearm, analysing the radius only, rather than radius and ulna together, lead to an underestimation of the skeletal benefits in gymnasts for the following parameters: BMC (-0.05 vs. +0.49 SD), ToA (+0.35 vs. +0.51 SD) and CoA (+0.09 vs. +0.47 SD).

Discussion

Pre-pubertal gymnastics participation at a non-elite level was associated with bone benefits to both the ulna and radius. At the distal forearm, bone benefits were more than twofold greater for the radius than ulna in bone mass, size and strength. Proximally, the ulna displayed greater exercise-induced benefits than the radius, which is consistent with a previous study conducted in retired elite gymnasts[6]. Skeletal benefits associated with gymnastics participation ranged from +5% to +16% for non-elite gymnasts compared with non-gymnasts. At the distal forearm, skeletal benefits were attributed to greater trabecular volumetric bone mineral density rather than bone geometry, whereas at the proximal forearm, skeletal benefits were largely due to a larger cross-sectional bone size. These results are consistent with those previously reported in racquet sports[13,15].

The gymnasts within the current study had greater bone strength than non-gymnasts at the distal and proximal forearm following training for approximately three years. These findings suggest that training at a moderate intensity rather than the high intensity reported by elite gymnasts, is sufficient in inducing skeletal benefits in upper limb bone mass, density, cross-sectional size and strength. These benefits emerged despite the upper limbs being exposed to lower ground reaction forces and frequency of impacts compared with the lower limbs[16,17]. These findings are supported by recent results obtained in recreational gymnasts and ex-gymnasts at the distal radius[4].

The skeletal benefits observed in non-elite gymnasts were achieved at both the proximal ulna and radius. Specifically, at the ulna, gymnasts had more bone mass, greater bone strength and a larger bone area (total and cortical) than the non-gymnast control group. At the radius, gymnasts also had a larger total bone size and strength than the non-gymnasts. While benefits were found at both the ulna and radius, the skeletal differences were more pronounced at the proximal ulna (Z-score+0.49 to +0.82 SD) than the proximal radius (Z-score-0.05 (NS) to +0.43

SD). These results strongly support previous findings on retired elite gymnasts who had started training during their pre-pubertal years[6]. The findings of this study therefore support the inclusion of the ulna in future investigations on gymnasts and more generally exercise-induced skeletal adaptations at the forearm, to limit the risk of error associated with skeletal benefits.

At the distal forearm, skeletal benefits in pre-pubertal non-elite gymnasts were only significant at the radius, which contrasts previous findings in adult retired elite gymnasts who showed skeletal benefits at the distal ulna[6]. We found pre-pubertal non-elite gymnasts had greater radial bone mass, trabecular bone mineral density and bone strength when compared with non-gymnasts, which is similar to what has previously been reported in pre-pubertal elite[1] and recreational gymnasts[4]. However, these benefits were not associated with an increase in cross-sectional bone size, which is consistent with previous reports in young gymnasts[1,3,4] but not with previous results in adult retired gymnasts[2,6]. The aforementioned findings suggest that gymnastics-induced skeletal differences at the distal forearm seem to vary between young girls exposed to short-term training and adults who have completed their career.

Differences in skeletal parameters observed at the distal radius between pre-pubertal and adult gymnasts may be the result of longitudinal growth. As long bones increase in length, new bone is continuously added between the growth plate and the metaphysis. At the junction of the metaphysis and the diaphysis, metaphyseal inwaisting occurs in which trabeculae are remodelled and cross-sectional bone size decreases through periosteal resorption, until it has reached the cross-sectional size of the diaphysis[12]. Measurements by pQCT at the distal forearm are performed in the metaphysis, i.e. a skeletal site at which the bone continually undergoes metaphyseal inwaisting. This might explain why pre-pubertal gymnasts do not experience a significant increase in bone size compared with non-gymnasts. In contrast, at the proximal forearm (diaphysis) where appositional bone growth occurs, pre-pubertal gymnasts experienced significant gains in cross-sectional bone size.

Another possibility to explain the lack of bone enlargement at the distal forearm in young gymnasts would be that the exposure to the weight-bearing component of gymnastics training in these young girls was too short and therefore primarily affected trabecular volumetric density. In support of this notion, it was suggested that repetitive loading in adult triple jumpers induced geometrical adaptations at a trabecular site (distal tibia), but possibly after the trabecular density reached its ceiling[18]. Alternatively, a previous study reported distal sites respond to loading by increasing trabecular density rather than bone cross-sectional area, potentially as a result of compressive loading rather than bending forces[13]. The short-term exposure to loading in the pre-pubertal gymnasts may also explain the relatively smaller magnitude of the skeletal benefits in the pre-pubertal non-elite gymnasts when compared with retired elite gymnasts[6]. Specifically, at the distal radius bone benefits ranged between Z-score +0.40 to +0.65 SD for the pre-pubertal gymnasts versus +0.7 to +2.1 SD for the retired elite gymnasts. At the proximal site, where the benefits were larger at the ulna than the radius, the magnitude of bone differences were +0.15 to +0.48 SD for the pre-pubertal gymnasts versus +1.0 to +1.6 SD for the adult retired gymnasts. Not only had the retired gymnasts participated in gymnastics from a very young age (5.8±0.9 years, on average) but they also maintained their training throughout pubertal growth. Similarly, results from tennis, another sport typically initiated at a young age, and squash players, found skeletal benefits to be larger in adults compared with young players[19] and larger in those who began sports participation before puberty as opposed to after[13].

In addition to their longer training history, adult retired elite gymnasts would have been exposed to a higher weekly training load inducing larger ground reaction forces[20,21] and increased muscle strength and power[22,23] compared with the non-elite gymnasts, all of which influence skeletal adaptations. It is unknown if the smaller bone benefits found in young non-elite gymnasts when compared with retired gymnasts are due to the shorter training history, lower training load and/or ground reaction forces, or a combination of these factors. Furthermore, peak in bone mineral accretion, experienced around the age of menarche[24], had not yet been reached by the young gymnasts in the present study.

This study presents several limitations. Due to the cross-sectional nature of the investigations, the possibility of a selection bias in the group of non-elite gymnasts cannot be ruled out. Cortical measurements were most likely affected by partial volume effect, which occurs when voxels at the bone edges are incompletely filled and cortical porosity, which cannot be assessed accurately by pQCT due to insufficient resolution. The underestimation of cortical density increases as cortical thickness decreases. This issue is more noticeable for cortices thinner than 2 to 2.5 mm[25-27]. At the proximal site, only two out of 58 gymnasts and three out of 28 non-gymnasts had radial cortical thickness greater than 2 mm, whereas 12 gymnasts and two non-gymnasts had ulnar cortical thickness greater than 2 mm. None of the participants had cortical thickness (radius or ulna) greater than 2.5 mm. Inaccuracies of cortical measurements are expected when investigating bones with a thin cortical shell.

Conclusion

Pre-pubertal non-elite gymnastics participation was shown to be associated with skeletal benefits at both the radius and ulna. The radius was found to be more responsive to gymnastic-specific loading at the distal forearm whereas the ulna had greater benefits at the proximal site, supporting previous findings in retired elite gymnasts. Although the skeletal benefits found at the proximal radius were significant in young non-elite gymnasts with 0.5 to 6 years of training history, the overall benefits were larger when skeletal differences in the proximal ulna were included. These findings suggest the ulna is worth investigating in future studies that aim to accurately quantify the skeletal adaptations induced by exercise.

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