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Original Article

# Gymnastics participation is associated with skeletal benefits in the distal forearm: a 6-month study using peripheral Quantitative Computed Tomography

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**Abstract**

**Objectives:** Musculoskeletal development of the upper limbs during exposure to weight-bearing loading is under-researched during early pubescent growth. The purpose was to assess the changes in upper body musculoskeletal strength in young girls following 6 months of non-elite gymnastics participation. **Methods:** Eighty-four girls, 6-12 years were divided into groups based on gymnastics participation: high-training (HGYM, 6-16 hr/wk), low-training (LGYM, 1-5 hr/wk), and non-gymnasts (NONGYM). Volumetric BMD, bone geometry, estimated bone strength and muscle size were assessed at the non-dominant forearm (4% and 66% radius and ulna) with pQCT. DXA assessed aBMD and body composition. Tests for explosive power, muscle strength, and endurance were also performed. **Results:** Interaction effects were observed in all variables at the 4% radius. At the 66% ulna, HGYM and LGYM had greater bone mass, size and bone strength than NONGYM, furthermore a dose-response relationship was observed at this location. Body composition was better for HGYM than LGYM and NONGYM, however muscle function was better for HGYM and LGYM than NONGYM. **Conclusion:** The greatest changes were obtained with more than one gymnastics class per week. Separating gymnastics participation-related changes from those associated with normal growth and development remains difficult, particularly at the 4% radius.

**Keywords:** Artistic Gymnastics, Upper Limb, Longitudinal, Musculoskeletal, Female

## Introduction

Participation in elite gymnastics may be related to positive musculoskeletal health outcomes[1,2] however, the injury risk[3,4] associated with the training volume and intensity (>25 hr/wk)[5] make it unsuitable for the promotion of physical activity within the general population. Non-elite gymnastics participation involves fewer training commitments, psychological demands, nutritional and hormonal disturbances, and a reduced prevalence of injuries compared with participation in elite gymnastics[4,6,7]. As a consequence, an increasing number of studies are investigating the association of non-elite gymnastics participation on skeletal properties[8-12].

Musculoskeletal relationships associated with non-elite gymnastics participation are expected to be smaller than relationships associated with elite gymnastics and may vary based on exposure to the sport. To detect these relationships, it is necessary to account for growth, maturation and other potential confounders in longitudinal investigations. Previous longitudinal studies on non-elite gymnasts used dual-energy X-ray absorptiometry (DXA)[11,13-15], a 2D imaging modality which cannot measure 3D bone density or geometry. In contrast, peripheral quantitative computed tomography (pQCT) is able to assess 3D total bone and compartmental properties. Despite slightly higher variability in pQCT than DXA, pQCT has previously been used in several cross-sectional studies in pre- and early pubertal gymnasts[10,16,17] and one longitudinal study on male and female pre-pubertal gymnasts[18].

The authors have no conflict of interest.

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The notion of the muscle-bone relationship is not new however, most studies use surrogate measures of muscle force and function such as lean mass when analysing the muscle-bone relationship[19-21]. Few studies have assessed actual muscle function in addition to bone health among young gymnasts[12,14,22]. One study reported changes in muscle function over time; reporting gymnasts had greater muscle strength than non-gymnasts at baseline however, no difference between groups was evident at follow-up[14].

The minimum amount of training necessary to induce positive musculoskeletal changes in young gymnasts is currently unknown. Reviews of exercise interventions in children and adolescents show two to three sessions per week are typically prescribed for improving musculoskeletal health[23,24]. However, gymnastics is associated with high-intensity loading, and a unique bilateral loading pattern of the upper and lower limbs, as opposed to the majority of sports that only load the lower limbs. Whether or not the same overall exposure, resulting from a single session of gymnastics per week (i.e. 2-3 hours) provides sufficient improvements in short-term musculoskeletal health benefits is unclear.

The aim of the study was to compare the changes in musculoskeletal parameters over six months in early pubertal female artistic gymnasts participating in different training volumes (high-10.5 hr/wk and low-3 hr/wk) with a group of age- and gender-matched non-gymnasts. Specifically, gymnasts were expected to have greater increases in upper limb muscle function and skeletal parameters than non-gymnasts. Furthermore, we hypothesized a dose-response relationship would emerge between gymnastics exposure and the increases in musculoskeletal parameters.

## Methods

### Study participants

Prior to participant recruitment, the study was approved by the University's ethics committee. Initially, 141 early pubertal girls were invited to participate in this longitudinal study. After obtaining informed parental consent and child assent, a total of 94 participants completed baseline assessments, three of whom were excluded as they did not meet the early pubertal selection criterion (≤ Tanner Stage II). Following six months of growth and development, 91 girls completed subsequent assessment. Seven girls dropped out at follow up as they were unable to attend scheduled appointments. There were no baseline-related bone differences between girls who dropped out of the study and those who completed the study. Therefore, 84 young girls were included in this study.

Participants were assigned to one of three groups based on their gymnastics participation: high-training gymnasts (HGYM; n=28), 6 to 16 hr/wk, low-training gymnasts (LGYM; n=28), 1 to 5 hr/wk and non-gymnasts (NONGYM; n=28). The cut-off point of 5 hr/wk, used to discriminate HGYM and LGYM, was chosen based on the number of training sessions per week: LGYM participated in one gymnastics class per week (never exceeding 5 hr/wk), whereas HGYM participated in more than one class per week (always exceeding 5 hr/wk). HGYM participants involved in the study were training 16 hr/wk or less, which is significant however, this involvement is still considered a non-elite level, and is associated with normal growth and maturation[25]. At study initiation, participants were healthy early pubertal girls, not taking any medication known to affect bone or muscle metabolism, and without a fracture to the upper limb within the previous 12 months. Gymnasts were recruited from local gymnastics centres and were training between 1 and 16 hr/wk. Gymnasts had trained for at least six months in the sport and were participating at a recreational or non-elite level. Non-gymnasts were involved in less than 4 hr/wk of organised physical activity outside school and were recruited via the "bring a friend" recruitment strategy.

### Setting

Recruitment took place over a nine-month period. The total duration of the study was 15 months. All assessments were conducted in the University's laboratory. The average time between baseline and follow up assessments was six months (range 5 to 8 months, mean 6.1, SD 0.82).

### Power analysis

To allow for the detection of significant differences in skeletal characteristics with a small estimated effect size ($d$=0.20), with a statistical power of 90% and a significance level of 0.05, the minimum total sample size was calculated to be 84 participants[26].

### Anthropometric assessment

A stadiometer (SECA height rod model 220, Hamburg, Germany) with an accuracy of 0.1 cm was used to measure standing and sitting height. Body mass was recorded using digital scales (A&D Company Ltd., Tokyo, Japan) with an accuracy of 0.05 kg.

### Body composition and areal Bone Mineral Density

Whole body areal bone mineral density (aBMD), bone mineral content (BMC), bone area, lean and fat mass were measured by dual-energy X-ray absorptiometry (DXA, Norland, XR-36 System, Fort Atkinson, Wisconsin). Body composition and bone parameters in the upper limb (including the humerus, ulna, radius, carpals, metacarpals and phalanges) were derived from the whole body scan. Measurements were performed at the predetermined scan mode (speed 180 mm/s, resolution 6.5 x 13.0 mm, source collimation 1.68 mm) with the analysis software provided by the manufacturer (2.5.3a). The same technologist conducted and analysed all DXA scans. The CV in our laboratory was obtained following scanning of nine healthy university students twice, following repositioning. Specifically, CV's were <1.8% for whole body and arm lean mass, aBMD, and BMC. Fat mass CV's were <3.5%.

## Volumetric bone mineral density, bone geometry and bone strength

Volumetric bone mineral density and bone geometry were measured by pQCT in participants' non-dominant forearm (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[27,28]. At the 4% and 66% sites tomographic slices of 2.3 mm thickness were obtained with a voxel size of 0.4 mm and scan speed of 15 mm/s. Image processing and the calculation of bone parameters were conducted using the manufacturer's software package (XCT version 5.50d).

At the 4% distal forearm, total bone mineral content (ToC), total bone area (ToA), total bone density (ToD), trabecular density (TrD) and bone strength index (BSI) were determined. The BSI was calculated as an estimation of bone strength and was determined using the following formula: $BSI = ToA * ToD^2$[29]. At the distal forearm, variables were calculated using contour and peel mode 1 with a threshold of 180 mg/cm$^3$.

At the 66% site, ToC, ToA, ToD, cortical area (CoA), cortical density (CoD), cortical thickness (CoTh), medullary area (MedA) and the polar strength strain index (SSI) were calculated. Cort mode 1 with a threshold of 711 mg/cm$^3$ was used for cortical bone and 280 mg/cm$^3$ for SSI, ToA and ToD calculations. Keeping the same mode, an additional threshold (40 mg/cm$^3$) was applied to remove the fat area from the total cross-sectional slice and obtain the muscle-bone area. Muscle cross-sectional area (MCSA) was calculated by subtracting the bone area from the muscle-bone area.

The same technologist conducted and analysed all pQCT analyses. Quality assurance checks of the pQCT device were regularly performed. A total of 48 scans were completed which represented three scans per participant at the 4% distal site and three scans per participant at the 66% site. Repeat measurements were not undertaken with children or adolescents due to a need to minimise cumulative radiation exposure. Scans were completed over two consecutive days by the same operator (DG). The CV for pQCT variables ranged from low (<1.5%; ToC, TrD), to medium (2-4%; CoA, SSI), to high (5-6%; ToA, ToD, CoD).

## Muscle function

*Muscle strength*

A hand grip dynamometer (Smedley's dynamometer TTM, Tokyo) was individually adjusted for participants. Participants held the dynamometer with their non-dominant arm extending downwards, away from the body[30], squeezing the device maximally for three seconds. Participants had two familiarisation trials. The best of the three trials was recorded.

*Explosive power*

The seated ball throw was adapted from a previous study[31]. Participants tried to throw the ball a distance of three meters, aiming their throw towards a target (located at the three meter mark). Throws were repeated three times and the best trial was recorded. The weight of the medicine ball was relative to 10% of the participant's body weight (range 2 to 5 kg).

*Muscle endurance*

In the absence of valid paediatric muscle endurance tasks[32] and to remove gymnastics-specific bias, two novel tasks for testing upper arm muscle endurance were devised and have previously been described in detail[33]. In brief, the first task required participants to perform a maximum number of successful 'weighted' arm sequences during a 30 second time period. The arm sequence involved touching the shoulders, reaching for a rod positioned above participants and laterally returning the arms to the sides. The weight applied to the arms (wrists) was relative to 5% of the participant's body weight.

The second task required participants to hold an upright static position using their arms to support their own body weight between two stabilised benches. The first two trials were used to pre-fatigue participants, lasting 30 seconds (if successful). The third and final trial required participants to hold the position to volitional failure. The successful time on the third attempt was recorded.

The inter-day CV for all muscle function tasks were calculated on a subsample of girls, one week apart. The CV for all muscle function tasks was ≤4.5%, falling below the acceptable reliability of <9%[34].

## Pubertal stage

Maturation was assessed using a proxy report of Tanner's five stage model for pubertal maturation[35]. Parents and daughters were asked to complete this questionnaire together. At baseline and follow-up participants with a combined Tanner score (breast + pubic hair development) ≤4 were included in this study.

## Calcium, protein and total caloric intakes

Calcium, protein and total caloric intake were estimated with a 3-day diet recall over two school days and one weekend day. During these three days, parents and daughters completed the questionnaire together. Data were then entered into FoodWorks (dietary-analysis software Xyris Software Pty. Ltd., Highgate Hill, QLD, Australia) and average intakes calculated.

## Questionnaires

Parents completed questionnaires about their daughter's training background, physical activity/exercise history, injury and health status. These answers were used to verify eligibility for study participation, participant grouping and monitor changes in activity patterns over the duration of the study.

## Statistical analyses

Statistical analyses were performed with SPSS for windows (version 18.0, SPSS Inc., Chicago, IL). Differences in mean

| | Non-Gymnasts (n=28) Baseline | Non-Gymnasts (n=28) 6MO | Low Gymnasts (n=28) Baseline | Low Gymnasts (n=28) 6MO | High Gymnasts (n=28) Baseline | High Gymnasts (n=28) 6MO | P Value Group | P Value Time | P Value Group*Time |
|---|---|---|---|---|---|---|---|---|---|
| **Age (y)** | 8.5 (8.0-9.0) | 9.1 (8.5-9.6) | 8.5 (7.9-8.9) | 8.9 (8.4-9.4) | 9.1 (8.6-9.6) | 9.6 (9.1-10.2) | 0.137 | <0.001[f] | 0.832 |
| **Standing Height (cm)** | 136.0 (133.3-138.7) | 138.7 (135.8-141.6) | 135.5 (132.7-138.2) | 138.6 (135.7-141.5) | 136.3 (133.6-139.0) | 138.9 (136.0-141.8) | 0.961 | <0.001[f] | 0.387 |
| **Sitting Height (cm)** | 67.7 (65.9-69.5) | 69.8 (68.1-71.5) | 67.4 (65.6-69.2) | 69.9 (68.1-71.6) | 68.1 (66.3-69.9) | 71.1 (69.4-72.8) | 0.674 | <0.001[f] | 0.513 |
| **Body Mass (kg)** | 32.1 (29.8-34.4) | 34.1 (31.5-36.7) | 31.4 (29.1-33.6) | 33.1 (30.6-35.7) | 30.7 (28.5-33.0) | 33.0 (30.4-35.6) | 0.776 | <0.001[f] | 0.484 |
| **Tanner Breast I (N, % stage I)** | 23 82% | 20 71% | 23 82% | 20 71% | 22 79% | 21 75% | 0.927 | 0.007[f] | - |
| **Tanner Pubic Hair I (N, % stage I)** | 28 100% | 24 89% | 27 96% | 27 96% | 25 89% | 22 79% | 0.163 | 0.005[f] | - |
| **Whole Body Lean Mass (kg)** | 19.0 (17.7-20.3) | 20.2 (18.6-21.7) | 19.6 (18.2-20.9) | 21.1 (19.4-22.8) | 20.3 (19.0-21.7) | 21.8 (20.2-23.3) | 0.372 | <0.001[f] | 0.566 |
| **Whole Body Fat Mass (kg)** | 9.3 (9.2-9.4) | 9.4 (9.2-9.5) | 9.2 (9.1-9.3) | 9.2 (9.1-9.4) | 9.0 (8.9-9.1) | 9.1 (8.9-9.2) | 0.029[d] | <0.001[f] | 0.270 |
| **Gymnastics Training (hr.wk$^{-1}$)** | - | - 3.1 (2.3-3.9) | 3.0 (2.1-3.8) | 10.5 (9.6-11.3) | 10.4 (9.5-11.3) | <0.001[abc] | 0.779 | 0.545 | - |

*Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P values represent group and time main effects as well as the interaction effect (group * time) for repeated measures ANOVA, except for Tanner stage where Kruskal-Wallis assessed group differences and Wilcoxon matched-pairs assessed changes over time. Pairwise comparisons following bonferroni adjusted ANOVA have only been reported in the absence of an interaction effect: [a]HGYM>NONGYM, [b]LGYM>NONGYM, [c]HGYM>LGYM, [d]NONGYM>HGYM, [e]NONGYM>LGYM, [f]6MO>Baseline p<0.05. Tanner scores for participants in stage one are reported as a proportion (number of participants) and percentage of participants.*

**Table 1.** Descriptive characteristics for early pubertal girls participating in low- and high-training artistic gymnasts and a non-gymnastic reference group.

| | Non-Gymnasts (n=28) Baseline | Non-Gymnasts (n=28) 6MO | Low Gymnasts (n=28) Baseline | Low Gymnasts (n=28) 6MO | High Gymnasts (n=28) Baseline | High Gymnasts (n=28) 6MO | P Value Group | P Value Time | P Value Group*Time |
|---|---|---|---|---|---|---|---|---|---|
| **WB BMD (g/cm²)** | 0.725 (0.702-0.749) | 0.741 (0.716-0.766) | 0.707 (0.682-0.732) | 0.717 (0.691-0.743) | 0.716 (0.693-0.739) | 0.727 (0.704-0.751) | 0.163 | <0.001[f] | 0.750 |
| **WB BMC (g)** | 1351.5 (1255.1-1447.8) | 1445.1 (1342.2-1548.1) | 1332.0 (1236.8-1427.2) | 1410.6 (1300.8-1520.5) | 1339.5 (1247.1-1431.9) | 1425.7 (1319.4-1532.0) | 0.215 | <0.001[f] | 0.628 |
| **Arms BMD (g/cm²)** | 0.451 (0.430-0.472) | 0.448 (0.428-0.467) | 0.448 (0.424-0.472) | 0.446 (0.422-0.470) | 0.434 (0.414-0.453) | 0.441 (0.434-0.458) | 0.874 | 0.898 | 0.684 |
| **Arms BMC (g)** | 142.5 (132.1-152.9) | 153.3 (141.3-165.4) | 152.3 (137.8-166.8) | 163.0 (144.3-181.6) | 154.4 (141.2-167.5) | 165.4 (150.4-180.4) | 0.004[a] | <0.001[f] | 0.974 |

*Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P values represent group and time main effects as well as the interaction effect (group * time) for repeated measures ANCOVA, adjusted for baseline differences in body mass. Pairwise comparisons following bonferroni adjusted ANCOVA have only been reported in the absence of an interaction effect: [a]HGYM>NONGYM, [b]LGYM>NONGYM, [c]HGYM>LGYM, [d]NONGYM>HGYM, [e]NONGYM>LGYM, [f]6MO>Baseline, p<0.05. WB BMD: Whole body bone mineral density; WB BMC: Whole body bone mineral content.*

**Table 2.** Bone mineral content and density results for dual-energy X-ray absorptiometry derived skeletal parameters of the whole body and arms.

and median in addition to Kolmogorov-Smirnov values were used to assess normal distribution[36]. Data were presented as mean±95% confidence intervals (CI). Non-parametric statistics were used for Tanner stage as it is a categorical variable. Differences in non-parametric statistics were calculated using Kruskal-Wallis to test for associations in frequency distributions between groups and Wilcoxon matched-pairs for changes over time. DXA assessment of lean and fat mass, pQCT measures of ToC, ToA, TrD, MedA and BSI at the 4% site as well as the static hold assessment were log10 transformed as they failed to meet criteria for normal distribution.

Musculoskeletal parameters were compared between groups

| Radius | Non-Gymnasts (n=27) Baseline | 6MO | Low Gymnasts (n=27) Baseline | 6MO | High Gymnasts (n=28) Baseline | 6MO | P Value Group | P Value Time | P Value Group*Time |
|---|---|---|---|---|---|---|---|---|---|
| **ToC (g/cm)** | 0.656 (0.597-0.714) | 0.699 (0.633-0.764) | 0.673 (0.619-0.726) | 0.729 (0.644-0.813) | 0.728 (0.670-0.786) | 0.874 (0.790-0.957) | 0.001 | <0.001 | <0.001 |
| **ToA (mm²)** | 243.97 (222.06-265.88) | 255.23 (233.14-277.32) | 230.22 (214.26-246.18) | 246.78 (222.29-271.27) | 238.34 (219.84-256.84) | 275.18 (253.47-296.89) | 0.124 | <0.001 | 0.001 |
| **ToD (mg/cm³)** | 275.32 (262.05-288.59) | 274.50 (263.58-285.42) | 295.52 (282.31-308.73) | 295.60 (281.91-309.29) | 306.44 (296.53-316.35) | 316.82 (305.07-328.56) | 0.001 | 0.442 | 0.033 |
| **TrD (mg/cm³)** | 209.98 (195.24-224.72) | 225.34 (209.41-241.26) | 222.62 (207.53-237.71) | 228.57 (208.72-248.43) | 230.65 (219.82-241.48) | 255.79 (241.63-269.95) | 0.014 | 0.002 | 0.009 |
| **BSI (mg/mm⁴)** | 17.76 (15.82-19.71) | 19.32 (16.99-21.65) | 20.19 (18.03-22.35) | 21.88 (18.54-25.22) | 21.20 (19.58-22.83) | 28.04 (24.49-31.59) | <0.001 | <0.001 | <0.001 |
| **Ulna** | | | | | | | | | |
| **ToC (g/cm)** | 0.313 (0.288-0.338) | 0.330 (0.294-0.366) | 0.308 (0.287-0.330) | 0.344 (0.300-0.388) | 0.327 (0.305-0.349) | 0.367 (0.337-0.397) | 0.114 | <0.001[f] | 0.234 |
| **ToA (mm²)** | 109.95 (102.30-117.6) | 111.94 (104.82-119.06) | 104.50 (97.80-111.21) | 106.37 (99.15-113.59) | 106.46 (99.08-113.83) | 116.29 (108.19-124.38) | 0.290 | <0.001 | 0.024 |
| **ToD (mg/cm³)** | 283.58 (273.71-293.44) | 282.40 (271.91-292.89) | 296.15 (283.35-308.95) | 303.68 (288.32-319.04) | 308.36 (299.86-316.86) | 313.97 (305.71-322.23) | 0.002[a] | 0.084 | 0.161 |
| **TrD (mg/cm³)** | 265.82 (248.65-282.99) | 263.47 (247.50-279.44) | 271.67 (255.27-288.07) | 269.78 (251.69-287.87) | 273.82 (261.63-286.00) | 291.01 (277.47-304.54) | 0.252 | 0.211 | 0.025 |
| **BSI (mg/mm⁴)** | 8.93 (8.01-9.84) | 9.37 (8.27-10.48) | 9.21 (8.32-10.10) | 10.35 (9.23-11.46) | 10.12 (9.30-10.93) | 11.59 (10.41-12.78) | 0.012[a] | <0.001[f] | 0.111 |

*Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P values represent group and time main effects as well as the interaction effect (group * time) for repeated measures ANCOVA, adjusted for baseline differences in body mass. Pairwise comparisons following bonferroni adjusted ANCOVA have only been reported in the absence of an interaction effect: [a]HGYM>NONGYM, [b]LGYM>NONGYM, [c]HGYM>LGYM, [d]NONGYM>HGYM, [e]NONGYM>LGYM, [f]6MO>Baseline, p<0.05. ToC: Total Bone mineral content; ToA: Total area; ToD: Total density: TrD: Trabecular density; BSI: Bone strength index.*

**Table 3.** Peripheral quantitative computed tomography results at the 4% forearm in three groups of early pubertal girls.

using repeated measures ANCOVAs, with adjustment for baseline assessment of body mass. Post hoc Bonferroni analyses were used to determine between-group differences. Results are displayed as main effects for time and gymnastics participation as well as the interaction effect (group*time). Where an interaction effect has been identified no main effects will be discussed. Statistical significance was set at an alpha level of 0.05 for all tests.

## Results

### Demographic Data

Interaction effects were not observed for any anthropometric or questionnaire data (Table 1). Time main effects were observed for all anthropometric data ($p<0.05$). There was no main effect for hours of gymnastics training ($p>0.05$). Gymnastics participation main effects were observed for whole body fat mass and hours of gymnastics training. NONGYM had more fat mass than HGYM ($p<0.05$). Hours of gymnastics training were different between all three groups (HGYM > NONGYM, LGYM > NONGYM, HGYM > LGYM, $p<0.05$). Training for the LGYM ranged from 1 to 5 hr/wk, whereas HGYM trained between 6 to 16 hr/wk. Previous gymnastics history (approximately three years of training) at study initiation was not different between gymnastics groups. NONGYM commonly participated in dancing, netball, soccer and swimming (range: 0 to 4 hr/wk). There were no main effects for calcium, protein or total caloric intake ($p>0.05$)

### Skeletal imaging: DXA and pQCT

There were no interaction effects for skeletal DXA variables ($p>0.05$, Table 2). All skeletal DXA variables, with the exception of Arms BMD, revealed a main effect for time (6MO >baseline, $p<0.05$). Arms BMC was the only skeletal DXA variable to show a main effect for gymnastics participation (HGYM >NONGYM, $p<0.05$).

The pQCT scans of one LGYM and one NONGYM participant were removed due to movement artifacts. Following body mass adjusted repeated measures ANCOVAs there were interaction effects for all pQCT variables at the 4% radius as well as ulna ToA and TrD ($p<0.05$, Table 3). As interaction ef-

| Radius | Non-Gymnasts (n=27) Baseline | 6MO | Low Gymnasts (n=27) Baseline | 6MO | High Gymnasts (n=28) Baseline | 6MO | P Value Group | P Value Time | P Value Group* Time |
|---|---|---|---|---|---|---|---|---|---|
| **ToC (g/cm)** | 0.605 (0.569-0.642) | 0.637 (0.592-0.682) | 0.599 (0.556-0.642) | 0.628 (0.578-0.678) | 0.625 (0.591-0.658) | 0.666 (0.629-0.704) | 0.087 | <0.001[f] | 0.216 |
| **ToA (mm²)** | 89.09 (84.11-94.07) | 94.58 (88.46-100.70) | 97.58 (89.05-106.10) | 100.39 (92.16-108.61) | 95.07 (89.80-100.34) | 100.04 (93.99-106.08) | 0.011[ab] | <0.001[f] | 0.471 |
| **ToD (mg/cm³)** | 683.96 (647.78-720.13) | 679.38 (637.64-721.13) | 621.32 (591.27-651.37) | 631.97 (596.26-667.69) | 662.34 (636.55-688.14) | 671.38 (641.06-701.70) | 0.032[e] | 0.106 | 0.149 |
| **CoA (mm²)** | 45.27 (42.42-48.12) | 46.71 (42.55-50.87) | 45.00 (41.74-48.26) | 46.99 (42.63-51.35) | 46.80 (43.82-49.77) | 51.42 (48.14-54.70) | 0.050 | <0.001 | 0.013 |
| **CoD (mg/cm³)** | 1048.98 (1029.61-1068.36) | 1043.53 (1022.82-1064.24) | 1012.25 (998.54-1025.96) | 1028.30 (1012.35-1044.34) | 1037.99 (1021.46-1054.52) | 1035.06 (1018.48-1052.73) | 0.064 | 0.267 | 0.006 |
| **CoTh** | 1.61 (1.49-1.72) | 1.62 (1.46-1.78) | 1.48 (1.39-1.57) | 1.55 (1.41-1.70) | 1.59 (1.50-1.69) | 1.72 (1.62-1.83) | 0.049[c] | 0.008[f] | 0.062 |
| **MedA** | 43.82 (39.00-48.65) | 47.87 (41.16-54.59) | 53.33 (46.14-60.51) | 53.39 (46.32-60.46) | 48.27 (44.17-52.38) | 48.60 (43.84-53.36) | 0.017[b] | 0.501 | 0.356 |
| **SSI (mm³)** | 124.85 (115.37-134.33) | 134.49 (120.43-148.56) | 134.09 (121.00-147.18) | 147.87 (130.91-164.83) | 139.75 (127.06-152.45) | 155.02 (139.93-170.12) | 0.002[ab] | <0.001[f] | 0.109 |
| **Ulna** | | | | | | | | | |
| **ToC (g/cm)** | 0.720 (0.675-0.766) | 0.747 (0.706-0.789) | 0.773 (0.725-0.822) | 0.792 (0.743-0.842) | 0.804 (0.766-0.843) | 0.840 (0.795-0.885) | <0.001[ab] | <0.001[f] | 0.585 |
| **ToA (mm²)** | 111.93 (103.89-119.97) | 115.27 (107.79-122.75) | 121.54 (112.56-130.53) | 122.35 (113.94-130.77) | 119.3 (111.52-127.07) | 120.97 (113.93-128.01) | 0.053 | 0.200 | 0.404 |
| **ToD (mg/cm³)** | 651.11 (619.65-682.57) | 655.90 (623.45-688.36) | 641.12 (620.42-661.82) | 652.64 (624.09-681.19) | 680.16 (657.40-702.91) | 698.03 (673.48-722.58) | 0.026[c] | 0.014[f] | 0.309 |
| **CoA (mm²)** | 50.57 (46.43-54.71) | 51.93 (47.15-56.72) | 57.46 (53.73-61.19) | 58.95 (54.10-63.80) | 60.67 (57.39-63.94) | 64.69 (60.31-69.06) | <0.001[abc] | 0.009[f] | 0.363 |
| **CoD (mg/cm³)** | 1028.33 (1005.23-1051.44) | 1034.32 (1010.80-1057.84) | 1006.90 (990.08-1023.71) | 1015.78 (997.13-1034.44) | 1016.68 (1001.24-1032.12) | 1026.98 (1012.66-1041.30) | 0.328 | 0.047[f] | 0.771 |
| **CoTh** | 1.59 (1.44-1.74) | 1.61 (1.44-1.77) | 1.72 (1.63-1.81) | 1.78 (1.62-1.93) | 1.87 (1.76-1.98) | 1.99 (1.86-2.12) | <0.001[ac] | 0.054 | 0.309 |
| **MedA** | 61.36 (52.58-70.14) | 63.34 (54.64-72.03) | 64.08 (57.41-70.75) | 63.40 (55.58-71.22) | 58.63 (51.66-65.60) | 56.29 (50.63-61.94) | 0.320 | 0.773 | 0.265 |
| **SSI (mm³)** | 161.10 (148.07-174.12) | 168.03 (153.45-182.60) | 185.94 (168.67-203.22) | 198.14 (176.32-219.96) | 185.83 (171.80-199.86) | 202.09 (182.17-222.02) | <0.001[ab] | 0.003[f] | 0.960 |

*Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P values represent group and time main effects as well as the interaction effect (group * time) for repeated measures ANCOVA, adjusted for baseline differences in body mass. Pairwise comparisons following bonferroni adjusted ANCOVA have only been reported in the absence of an interaction effect: [a]HGYM>NONGYM, [b]LGYM>NONGYM, [c]HGYM>LGYM, [d]NONGYM>HGYM, [e]NONGYM>LGYM, [f] 6MO>Baseline, p<0.05. ToC: Total bone mineral content; ToA: Total area: ToD: Total density; CoA: Cortical area; CoD: Cortical density; CoTh: Cortical thickness; MedA: Medullary area; SSI: Strength strain index.*

**Table 4.** Peripheral quantitative computed tomography results at the 66% forearm in three groups of early pubertal girls.

fects may contradict the interpretation of the main effects, the main effects for these variables have not been highlighted. At the 4% ulna ToC and BSI had a main effect for time (6MO >baseline, p<0.05). The only variables to display main effects for gymnastics participation were ToD and BSI at the ulna where HGYM were greater than NONGYM (p<0.05).

At the 66% site CoD and CoA at the radius were the only variables with interaction effects (p<0.05, Table 4). At the radius time main effects were observed for ToC, ToA, CoTh and SSI (p<0.05). At the ulna time main effects were observed for ToC, ToD, CoA, CoD and SSI (p<0.05). All main effects for time were higher at 6MO than baseline. At the 66% radius gymnastics participation main effects were observed for ToA, ToD, CoTh, MedA and SSI (p<0.05). At this site, HGYM and LGYM had a greater ToA and SSI than NONGYM. LGYM also had a greater MedA than NONGYM. HGYM had a bigger

| | Non-Gymnasts (n = 28) Baseline | Non-Gymnasts (n = 28) 6MO | Low Gymnasts (n=28) Baseline | Low Gymnasts (n=28) 6MO | High Gymnasts (n=28) Baseline | High Gymnasts (n=28) 6MO | P Value Group | P Value Time | P Value Group* Time |
|---|---|---|---|---|---|---|---|---|---|
| Arm LM | 1531.07 (1403.89-1658.25) | 1668.81 (1496.92-1840.71) | 1638.11 (1498.61-1777.61) | 1811.20 (1614.72-2007.68) | 1820.13 (1682.74-1957.51) | 1974.00 (1786.51-2161.49) | <0.001[ac] | <0.001[f] | 0.995 |
| MCSA | 1565.29 (1484.18-1646.40) | 1647.90 (1543.78-1752.02) | 1607.17 (1498.35-1715.98) | 1702.44 (1582.86-1822.02) | 1743.35 (1653.30-1833.39) | 1863.38 (1756.63-1970.14) | <0.001[ac] | <0.001[f] | 0.318 |
| Grip Strength | 13.93 (12.81-15.05) | 16.27 (14.86-17.68) | 14.73 (13.12-16.35) | 17.07 (15.41-18.74) | 15.55 (14.27-16.82) | 17.20 (16.00-18.39) | 0.037[a] | <0.001[f] | 0.306 |
| Ball Throw | 1.70 (1.60-1.81) | 1.78 (1.67-1.88) | 1.86 (1.75-1.97) | 1.92 (1.81-2.02) | 1.99 (1.90-2.09) | 1.98 (1.88-2.07) | <0.001[ab] | 0.149 | 0.191 |
| Arm Seq | 18.16 (16.43-19.88) | 20.71 (18.80-22.63) | 21.12 (19.46-22.78) | 23.73 (21.81-25.65) | 23.98 (22.31-25.66) | 25.63 (23.88-27.37) | <0.001[ab] | <0.001[f] | 0.477 |
| Static Hold | 34.71 (25.21-44.20) | 40.04 (30.38-49.69) | 51.58 (39.93-63.23) | 78.50 (66.42-90.58) | 71.53 (58.33-84.74) | 115.96 (92.19-139.74) | <0.001[ab] | <0.001[f] | 0.076 |

*Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P values represent group and time main effects as well as the interaction effect (group * time) for repeated measures ANCOVA, adjusted for baseline differences in body mass. Pairwise comparisons following bonferroni adjusted ANCOVA have only been reported in the absence of an interaction effect: [a]HGYM>NONGYM, [b]LGYM>NONGYM, [c]HGYM>LGYM, [d]NONGYM>HGYM, [e]NONGYM>LGYM, [f]6MO>Baseline, p<0.05. Arm LM: Arm lean mass; MCSA: Muscle cross-sectional area; Arm Seq: Arm sequence.*

**Table 5.** Muscle structure and function in high- and low-training gymnasts and a non-gymnast reference group.

CoTh than LGYM and NONGYM had a higher ToD than LGYM. At the 66% ulna gymnastics participation had main effects for ToC, ToD, CoA, CoTh and SSI (p<0.05). At this site HGYM had greater ToC, CoA, CoTh and SSI than NONGYM. LGYM had higher ToC, CoA and SSI than NONGYM. HGYM had higher ToD, CoA and CoTh than LGYM.

## Lean mass and muscle function

There were no interaction effects for any lean mass or muscle variables outlined in Table 5 (p>0.05). With the exception of the ball throw, all other variables had a main effect for time (6MO>baseline, p<0.05). Gymnastics participation had a main effect for all variables (p<0.05). HGYM had greater arm lean mass, MCSA, grip strength, ball throw, number of arm sequences and static hold time than NONGYM. LGYM had greater ball throw, number of arm sequences and static hold time than NONGYM. HGYM had greater arm lean mass and MCSA than LGYM.

## Discussion

Six months of involvement in non-elite artistic gymnastics may be associated with upper limb musculoskeletal benefits. Separating gymnastics participation-related changes from those associated with normal growth and development remains difficult, particularly at the 4% radius. Participation in one gymnastics class per week (3 hr/wk) was associated with greater musculoskeletal parameters than non-gymnasts at the 66% site. While both high- and low-training gymnasts had greater estimates of bone strength than non-gymnasts at the 66% site, the greatest skeletal changes were observed in the high-training gymnasts (6 to 16 hr/wk). In addition to bone, muscle function (power and endurance) was greater for gymnasts than non-gymnasts; and MCSA and arm LM were greater for high- than low-training gymnasts and non-gymnasts.

Over the duration of the study the largest changes were observed at the 4% radius; however, the interaction effects observed in these parameters mean relationships between gymnastics participation and skeletal outcome cannot be interpreted independent of growth. The participants within this study were early pubertal. During this time of growth, bones grow in length and metaphyseal inwaisting occurs. Therefore, it is not unexpected that bone relationships at the 4% site occur in the presence of normal growth and development, demonstrated by a main effect for time.

Between-group differences were observed at the proximal ulna. Specifically, at the 66% ulna gymnasts had greater total bone mass (ToC), cortical bone size and bone strength than non-gymnasts. These results are consistent with previous cross-sectional gymnastics studies, showing skeletal benefits at the 66% ulna[37,38] and support the inclusion of the ulna in future gymnastics-based studies.

High-training gymnasts had greater bone strength than non-gymnasts. At the 66% site low-training gymnasts had greater bone strength than non-gymnasts. At study initiation there were only bone strength-based differences between high-training gymnasts and non-gymnasts; with no significant differences observed between low-training gymnasts and non-gymnasts[33]. A cross-sectional pQCT study in recreational gymnasts, who had a similar training history, reported differences in bone strength between gymnasts and non-gymnasts at the distal radius, but no differences in bone strength at the shaft[10]. These results combined with our findings suggest that benefits in bone strength at the shaft may take longer to occur than benefits in metaphyseal bone.

Our results show a dose-response relationship between gymnastics participation and bone size (ulna CoA) as well as arm lean mass and muscle cross sectional area, where participation in more than one gymnastics class per week was associated with additional changes in musculoskeletal health. Previous non-elite gymnastics studies assessing different weekly training exposure reported a dose-response relationship benefiting gymnasts with greater weekly training commitments[11,12]. These studies found high-training gymnasts had greater DXA-derived bone density[12] and forearm bone area[11] over both low-training gymnasts and non-gymnasts. Our DXA results differ. We did not find greater increases in whole body BMC or aBMD over six months among gymnasts compared with non-gymnasts. Our findings may be explained by the shorter follow up period[11] or the younger age of the participants[12].

To the best of the authors' knowledge, the only other longitudinal study to investigate musculoskeletal health in pre- and early pubertal gymnasts using pQCT tested the effects of calcium supplementation on gymnastics-induced skeletal benefits[18]. At the distal radius, the gymnasts within the calcium study showed total density changes of 2 and 8 mg/mm$^3$ over 12 months (calcium and placebo, respectively)[18]. The high-training gymnasts within our study had changes of 1 mg/mm$^3$ over the six-month period. In addition, the six-month changes observed at the bone shaft in this study were consistent with those previously reported for bone strength, total and cortical cross-sectional bone area[18]. The slight discrepancies between studies are likely explained by the differences in the skeletal sites scanned (66% vs. 50%), the shorter duration of the follow-up (6-months vs. 12-months), and the sex of the gymnasts (female vs. male and female gymnasts). The relatively comparable results between studies suggested early pubertal female gymnasts may not have to participate in gymnastics at an elite level (>25 hr/wk), consisting of high training loads and intensities, to acquire skeletal benefits.

Previous research reported differences between high- and low-training gymnasts for muscle function, but not lean mass[12]. We found DXA-derived differences in lean mass and pQCT-derived muscle cross sectional area between high- and low-training gymnasts with no differences between gymnastics groups for muscle function. While high-training gymnasts had more lean mass and a larger muscle cross sectional area than low-training gymnasts, muscle function (strength, power and endurance) was not different between gymnastics groups. Therefore, studies should use actual rather than surrogate measures of muscle force and function to assess the muscle-bone relationship.

The novel approaches to assess muscle function and the inclusion of the ulna were unique components of the current study. Non-elite level of participation, particularly one gymnastics class per week, is more realistic and attainable for the majority of young females, compared with elite participation. While one class of gymnastics participation (3 hr/wk) provided skeletal benefits at the 66% forearm, explosive power and muscle endurance, a dose-response relationship emerged. Bone density (ToD), cortical area and thickness were greater for gymnasts averaging 10.5 hr/wk of training, at least at the 66% site.

Longitudinal studies offer opportunities to understand more about the musculoskeletal benefits associated with gymnastics training beyond growth. However, the short duration of this longitudinal study presents as a limitation. Additional longitudinal research following pre-pubertal gymnasts through pubertal growth and into retirement would be ideal. While the follow-up interval was not statistically different between groups, there was a trend for the non-gymnasts to come back after their six month anniversary date (six months from baseline testing) and the low-training gymnasts to come in prior to their anniversary date. This may have resulted in the non-gymnasts undergoing additional growth and development compared with the low-training gymnasts. In addition, the partial volume effect may have influenced the pQCT results of this study[39]. None of the participants had a cortical thickness (radius or ulna) greater than 2.5 mm. While pQCT has advantages over DXA in paediatric studies, results may be influenced by movement of participants and positional inconsistencies associated with longitudinal bone growth[40,41]. Furthermore, biochemical analyses of bone formation, absorption and maturation would have strengthened our results.

## Conclusions

Artistic gymnastics is a unique, bilateral, weight-bearing sport. Even at a low intensity (3 hr/wk), habitual loading may be associated with musculoskeletal health benefits to the upper limbs at the 66% site. However, the greatest skeletal changes were observed following more than one gymnastics class per week (10.5 hr/wk). Separating gymnastics participation-related changes from those associated with normal growth and development remains the greatest challenge, particularly at the 4% radius.

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