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Site-specific advantages in skeletal geometry and strength at the proximal femur and forearm in young female gymnasts ☆

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ABSTRACT

Purpose: We evaluated site-specific skeletal adaptation to loading during growth, comparing radius (RAD) and femoral neck (FN) DXA scans in young female gymnasts (GYM) and non-gymnasts (NON).
Methods: Subjects from an ongoing longitudinal study (8–26 yr old) underwent annual DXA scans (proximal femur, forearm, total body) and anthropometry, completing maturity and physical activity questionnaires. This cross-sectional analysis used the most recent data meeting the following criteria: gynecological age ≤2.5 yr post-menarche; and GYM annual mean gymnastic exposure ≥5.0 h/wk in the prior year. Bone geometric and strength indices were derived from scans for 173 subjects (8–17 yr old) via hip structural analysis (femoral narrow neck, NN) and similar radius formulae (1/3 and Ultradistal (UD)). Maturity was coded as M1 (Tanner I breast), M2 (pre-menarche, ≥Tanner II breast) or M3 (post-menarche). ANOVA and chi square compared descriptive data. Two factor ANCOVA adjusted for age, height, total body non-bone lean mass and percent body fat; significance was tested for main effects and interactions between gymnastic exposure and maturity.
Results: At the distal radius, GYM means were significantly greater than NON means for all variables ($p<0.05$). At the proximal femur, GYM exhibited narrower periosteal and endosteal dimensions, but greater indices of cortical thickness, BMC, aBMD and section modulus, with lower buckling ratio ($p<0.05$). However, significant interactions between maturity and loading were detected for the following: 1) FN bone mineral content (BMC) and NN buckling ratio (GYM BMC advantages only in M1 and M3; for BMC and buckling ratio, M1 advantages were greatest); 2) 1/3 radius BMC, width, endosteal diameter, cortical cross-sectional area, and section modulus (GYM advantages primarily post-menarche); and 3) UD radius BMC and axial compressive strength (GYM advantages were larger with greater maturity, greatest post-menarche).
Conclusions: Maturity-specific comparisons suggested site-specific skeletal adaptation to loading during growth, with greater advantages at the radius versus the proximal femur. At the radius, GYM advantages included greater bone width, cortical cross-sectional area and cortical thickness; in contrast, at the femoral neck, GYM bone tissue cross-sectional area and cortical thickness were greater, but bone width was narrower than in NON. Future longitudinal analyses will evaluate putative maturity-specific differences.

Abbreviations: DXA, dual energy X-ray absorptiometry; aBMD, areal bone mineral density; BMC, bone mineral content; Area, bone projected area; HSA, DXA hip structural analysis; RAD, radius; GYM, gymnasts; NON, non-gymnasts; FN, femoral neck; NN, femoral narrow neck; GYMHRS, annual mean hours per week gymnastic training for the year prior to the DXA scan; h/wk, hours per week; pQCT, peripheral quantitative computed tomography; MAT, maturity level; M1, physical maturity level 1 (pre-menarche, Tanner breast stage I); M2, physical maturity level 2 (pre-menarche, Tanner breast stage II or greater); M3, physical maturity level 3 (post-menarche); 1/3 DXA, 1/3 distal region of interest for the radial diaphysis; MEN, menarche status; UD, DXA, ultradistal region of interest for the radial metaphysis; nbFFM, DXA total body, non-bone, lean mass; CVs, coefficients of variation; ANOVA, analysis of variance; ANCOVA, analysis of covariance; VIF, variance inflation factor; BMI, body mass index; Z, section modulus; ED, endosteal diameter; cCSA, cortical cross-sectional area; IBS, index of structural strength in axial compression; CT, cortical thickness; PBF, percent body fat; NN bCSA, narrow neck bone tissue cross-sectional area; NN BR, narrow neck buckling ratio.

☆ All authors have no conflicts of interest.

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Introduction

The forearm and hip are major sites of osteoporotic fracture, together contributing over one third of the U.S. total (297,000 hip; 397,000 forearm) [1]. Furthermore, the distal radius is a common fracture site throughout life, with a peak in incidence occurring around the time of peak height velocity [2,3]. Thus, improvement of proximal femur and radius skeletal strength through non-pharmacological means is a vital strategy for reduction of the population fracture burden. Optimal physical activity exposure during growth may accomplish this aim, yielding long term bone strength benefits.

Supporting this premise, our group has published prospective, longitudinal evidence that gymnastics exposure during growth is associated with elevated DXA (dual X-ray absorptiometry) areal bone mineral density (aBMD), bone mineral content (BMC) and bone projected area (Area) at the distal radius/forearm, indicating persistent skeletal strength benefits at this important site [4,5]. The extreme model of artistic gymnastics is associated with uniquely exaggerated loads at both the non-dominant radius and the lower extremity [6–8]. Thus, observational studies of the gymnastic loading model provide the opportunity to evaluate skeletal adaptation to loading via site-specific DXA indices of bone geometry, density and associated theoretical skeletal strength at both the radius and the proximal femur.

Although cross-sectional studies have reported advantages in standard DXA outcomes for gymnasts (GYM) compared to non-gymnasts (NON) [9–14], few studies have evaluated indices of bone geometry and strength. Most bone geometric studies in women exposed to gymnastics have been performed at the forearm, often reporting greater indices of total bone size and strength in GYM and ex-GYM than NON [8,15–24]. Although numerous studies have reported greater femoral neck aBMD in GYM than NON, to our knowledge, only two studies have specifically evaluated indices of femoral neck geometry and strength [25,26]. Both studies reported greater indices of bone strength but lower sub-periosteal width in GYM than NON, using hip structural analysis (HSA) [25,26]; one other study has reported lower femoral neck projected area in GYM versus NON [27]. We are not aware of any published studies that have compared indices of bone geometry and strength at these two distinct sites, evaluating the effects of loading at both the forearm and the proximal femur, while accounting for variation in physical maturity.

This paucity of evidence limits our understanding of bone properties in GYM compared to NON, as available evidence is comprised of results from a variety of different methodologies, physical maturity groupings, and skeletal sites [8]. Therefore, to address shortcomings in current knowledge, we evaluated site-specific skeletal adaptation to loading during growth, comparing radius (RAD) and proximal femur DXA scans in young female GYM versus NON, and accounting for physical maturity variation from pre-puberty through post-menarche (Tanner breast stages I through V). We evaluated standard DXA outcomes of aBMD, BMC and projected area, as well as DXA-derived indices of bone geometry and strength [28,29]. We tested three related hypotheses, based upon existing literature: 1) GYM exhibit significant advantages in indices of bone mass, geometry, areal density and strength for both the radius and the femoral neck; 2) differences are of greater magnitude at the non-dominant distal radius than at the femoral neck; and 3) although GYM exhibit advantages in theoretical bone strength at both sites, GYM periosteal width is greater at the radius and narrower at the femoral narrow neck.

Methods

Recruitment

In accordance with the Declaration of Helsinki and with the approval of our Institutional Review Board, prior to participation, subjects provided written, informed consent or assent with parental consent, as appropriate based on subject age. Subjects were enrolled in 3 separate cohorts, with GYM recruited from local gymnastic schools and NON recruited from local private schools, investigator contacts and University newletters: Cohort 1, 1997–8 (initial NON n = 25, GYM n = 55; current analysis: NON n = 25, GYM n = 50.); Cohort 2, 2002–2003 (initial NON n = 25, GYM n = 15; current analysis: NON n = 23, GYM n = 14); and Cohort 3, 2008–2009 (initial NON n = 30, GYM n = 50; current analysis: NON n = 29, GYM n = 32). Numbers were lower in this analysis than at initial enrollment due to failure to meet gymnastic exposure criteria or incomplete data for focal variables.

Study design

Participants from our ongoing longitudinal study (8–26 yr old) underwent annual DXA scans (proximal femur, forearm, total body). On a semi-annual basis, height, weight and waist circumference were measured; calendar-based physical activity questionnaires and maturity questionnaires were completed [4]. The latter yielded self-reported Tanner breast and pubic stages, date of menarche, and subsequent gynecological age (years post-menarche) [4]. This cross-sectional analysis used the most recent complete data for which subjects exhibited a gynecological age no greater than 2.5 yr. GYM were included if they had annual mean gymnastic exposure for the year prior to the DXA scan greater than or equal to 5.0 h/wk; in cases where subjects had multiple valid years of “GYM” data, the latest year with the most consistent training levels was used (to alleviate the possible influence of de-training effects related to injuries/illness).

Due to the cross-sectional nature of this analysis, we cannot determine causal relationships between factors and skeletal development within individuals across time. In this study, we will refer to the statistical “effects” of loading, estrogen exposure and their interaction as suggested by the results of cross-sectional comparisons.

Physical activity quantification

We used annual mean gymnastic exposure for the year prior to the DXA session as our metric of gymnastic exposure dose (GYMHRS, h/wk), in part, because GYMHRS was the most reliably acquired data. GYMHRS was either recorded prospectively on a training calendar (early years Cohort 1) or recorded at measurement sessions to summarize the preceding 6–12 months (later years, Cohort 1; Cohorts 2 and 3). In contrast, age at training initiation and long-term training history were recalled up to 15 years post-hoc. Furthermore, within and between individuals, training intensity between training initiation and the focal DXA varied markedly (e.g. <2 h/wk for 4 years, increasing to 12 h/wk over 3 subsequent years versus >8 h/wk within the 1st year training). Thus, GYMHRS was employed to minimize the influence of recall bias.

NON were not sedentary controls; they participated in a variety of physical activities, including *<2 h/wk of gymnastics training* (in a few cases). Subjects who exceeded an average of 2 h/wk of gymnastics over the prior year, but did not achieve 5.0 h/wk, were excluded from analysis. This exposure contrast has been associated with significant differences in DXA and peripheral quantitative computed tomography (pQCT) outcomes in related samples [19,20].

Physical maturity evaluation

Menarche status is known to be influential in skeletal development and loading associations [4,5,28], but distinctions between pre-pubertal, pubertal pre-menarcheal and post-menarcheal subjects have not been evaluated in a study on gymnastic loading. Accordingly, physical maturity status was evaluated in two ways: 1) maturity level (MAT) was coded as M1 (pre-menarche, Tanner breast stage I (all