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Site-specific, adult bone benefits attributed to loading during youth: A preliminary longitudinal analysis

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ABSTRACT

We examined site-specific bone development in relation to childhood and adolescent artistic gymnastics exposure, comparing up to 10 years of prospectively acquired longitudinal data in 44 subjects, including 31 non-gymnasts (NON) and 13 gymnasts (GYM) who participated in gymnastics from pre-menarche to ≥1.9 years post-menarche. Subjects underwent annual regional and whole-body DXA scans; indices of bone geometry and strength were calculated. Anthropometrics, physical activity, and maturity were assessed annually, coincident with DXA scans. Non-linear mixed effect models centered growth in bone outcomes at menarche and adjusted for menarcheal age, height, and non-bone fat-free mass to evaluate GYM-NON differences. A POST-QUIT variable assessed the withdrawal effect of quitting gymnastics. Curves for bone area, mass (BMC), and strength indices were higher in GYM than NON at both distal radius metaphysis and diaphysis ($p < 0.0001$). At the femoral neck, greater GYM BMC ($p < 0.01$), narrower GYM endosteal diameter ($p < 0.02$), and similar periosteal width ($p = 0.09$) yielded GYM advantages in narrow neck cortical thickness and buckling ratio (both $p < 0.001$; lower BR indicates lower fracture risk). Lumbar spine and sub-head BMC were greater in GYM than NON ($p < 0.036$). Following gymnastics cessation, GYM slopes increased for distal radius diaphysis parameters ($p \leq 0.01$) and for narrow neck BR ($p = 0.02$). At the distal radius metaphysis, GYM BMC and compressive strength slopes decreased, as did slopes for lumbar spine BMC, femoral neck BMC, and narrow neck cortical thickness ($p < 0.02$). In conclusion, advantages in bone mass, geometry, and strength at multiple skeletal sites were noted across growth and into young adulthood in girls who participated in gymnastics loading to at least 1.9 years post-menarche. Following gymnastics cessation, advantages at cortical bone sites improved or stabilized, while advantages at corticocancellous sites stabilized or diminished. Additional longitudinal observation is necessary to determine whether residual loading benefits enhance lifelong skeletal strength.

1. Introduction

Adolescence is a crucial period for bone acquisition, with nearly half of adult bone mass acquired in the 4 years surrounding menarche [1–3]. Therefore, modifiable factors contributing to peak bone mass, such as diet and physical activity, may be most influential during this maturational period [4–6]. High-impact physical activity, such as gymnastics, is considered particularly osteogenic, yielding greater bone gains than cyclic loading activities, such as distance running, and non-weight-bearing activities, such as swimming [7–10]. Work by our group and others suggests that artistic gymnastics exposure is associated with site-specific skeletal benefits in bone mass and geometry, yielding advantages in theoretical bone strength of 4–56% [11–17].

Prospective longitudinal evidence from Bailey et al. has associated higher physical activity participation with greater bone mass gains (16% LSBMC, 11% FNBMC) from 1 year pre- to 1 year post-PHV [18]. Similarly, work by Gunter et al. demonstrated adolescent retention of subtle skeletal advantages 7 years after a 7-month jumping intervention that was administered pre-PHV (retained 1.4% advantage, total hip BMC) [19]. In a prior longitudinal analysis, we reported that pre-menarcheal gymnastics exposure for at least 2 years at ≥6 h per week, ceased circum-menarche, was associated with significant advantages over non-gymnasts for radius bone mass, size, and areal density over a growth curve that extended to at least 4 years post-menarche [20]. These studies suggest that pre-pubertal and early pubertal activity exposure may yield long-term skeletal advantages.

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The primary aim of the present study was to evaluate associations between maturity-specific loading exposure and site-specific bone development over a broad span of childhood and adolescent growth. We analyzed prospective, longitudinal DXA data representing up to 10 years of growth and maturation. We compared girls who were exposed to substantial gymnastics training before and after menarche (GYM) to girls without substantial gymnastics exposure (NON). Our analyses account for variability in biological age, body size, and non-bone fat-free mass in a time-varying context, adjusting for age at menarche as an indicator of maturational timing. We hypothesized that girls who participated in gymnastics training would demonstrate site-specific advantages in bone geometry, density, and strength indices, over this entire period of bone formation and maintenance, compared to those who did not. Furthermore, we hypothesized that bone geometric benefits would persist after cessation of gymnastic training, whereas bone mineral content benefits would deteriorate subtly over time post-cessation, such that loading advantages averaged over the entire growth curve would remain significant.

2. Methods

2.1. Subjects and study design

Study protocol was approved by the Institutional Review Board at SUNY Upstate Medical University (5332F, 2011–2), conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. Subjects and parents/guardians provided written, informed assent and consent, as appropriate for subject age; subjects provided written, informed consent to continue the study after their 18th birthday.

The 44 subjects included in the current analysis are a subset from an existing longitudinal study (1997–present) designed to observe skeletal growth and adaptation in a large group of young female gymnasts (GYM) and non-gymnasts (NON). Subjects were enrolled in 2 cohorts: Cohort 1, 1997–8 (initial GYM $n = 51$, NON $n = 31$; current analysis: GYM $n = 7$, NON $n = 13$), and Cohort 2, 2002–2003 (initial GYM $n = 12$, NON $n = 28$; current analysis: GYM $n = 6$, NON $n = 18$). As subjects in the 1997–8 cohort were originally recruited for an 18-month pilot study, many withdrew from the study after this pilot period.

For the present analysis, subjects were included if they provided ≥3 DXA scans with associated data, date of menarche, and date of gymnastics cessation (if applicable). Subjects were excluded if they ceased gymnastics for ≥1 year then resumed participation at a later date, they participated in long-term low-level or sporadic gymnastics training (multiple years at 1–4 h/wk) and/or they quit gymnastics earlier than 18 months post-menarche (GYNAGE +1.5). One additional non-gymnast was excluded due to thyroid cancer diagnosis, and two non-gymnasts were excluded due to concerns about female athlete triad. Cohort composition is detailed in the CONSORT diagram, Fig. 1.

Previous evaluation for the possibility of selection bias, based upon continued study participation, has been completed in our overall study cohort. There were no differences in baseline characteristics for age, height, weight, BMI, sub-head BMC, sub-head lean mass or percent body fat, or age at menarche, between those who were included in these analyses and those who were excluded. Furthermore, there were no differences in these characteristics between included subjects who provided 3–6 measurement points versus those who provided 7–10 measurement points.

Gymnasts were recruited from local gymnastics clubs; age, size, and maturity-matched non-gymnasts were recruited from local grade schools. Subjects underwent annual DXA scans (whole body, forearm, hip, lumbar spine). Anthropometrics [21], physical activity, and maturity were assessed semi-annually until age 18, after which only annual assessments were obtained, coincident with DXA scans.

2.2. Physical maturity evaluation

Chronologic age was determined by subtracting measurement date from birthdate (recorded at enrollment) and reported to the nearest 0.1 year. Self-reported age at menarche (queried semi-annually until positive) was used to calculate gynecological age for each measurement point (GYNAGE: years pre- (−) or post- (+) menarche (time zero), calculated as measurement date − menarche date, reported to the nearest 0.1 year). Beginning in 2006, subjects were specifically queried regarding menstrual regularity/irregularity and oral contraceptive use at each measurement session; prior to this date, this information is incomplete.

2.3. Physical activity quantification

Investigator-administered questionnaires were used to record average hours per week of organized non-aquatic physical activity (including gymnastics) for the intervals between assessments (semi-annually or annually). A similar methodology was validated in a subset of the

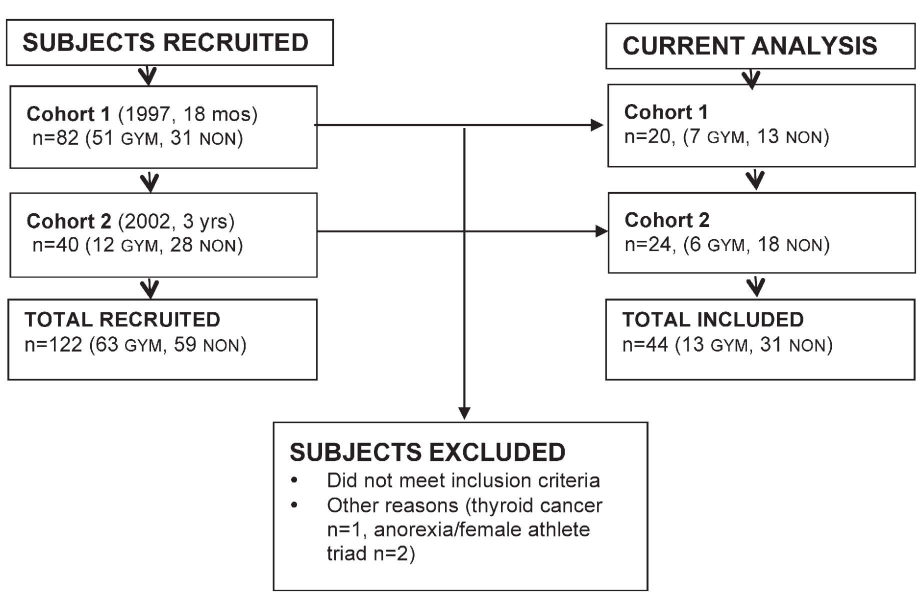

Fig. 1. *CONSORT diagram.* Subjects were recruited in two cohorts and included in the current analysis as follows (GYM = gymnast; NON = non-gymnast).