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Sustained skeletal benefit from childhood mechanical loading

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Abstract

Summary—Preliminary prospective, longitudinal results suggest that pre-menarcheal exposure to artistic gymnastics is associated with greater radius BMC, aBMD, and projected area throughout growth and into early adulthood, more than 4 years after activity cessation. Any loss of benefit associated with de-training appears to be temporary.

Introduction—Mechanical loading may enhance bone accrual during growth, but prospective evidence of benefit retention is limited. This prospective, longitudinal cohort study tests whether gymnastics is linked to distal radius advantages during growth and four or more years post-training cessation.

Methods—Semi-annually, female ex/gymnasts and non-gymnasts underwent height and weight measurements; questionnaires assessed calcium intake, physical activity, and maturation. Annual dual energy X-ray absorptiometry scans (Hologic QDR 4500W) measured total body fat-free mass, skull areal density (aBMD), and bone mineral content (BMC); forearm scans measured ultradistal and 1/3 radius area, BMC, and aBMD. Analysis inclusion criteria were: (1) achievement of gynecological age >4 years and (2) for gymnasts, >2 years of pre-menarcheal training (>6 h/week), ceasing between 0.5 year pre-menarche and 1 year post-menarche. Hierarchical linear modeling (HLM v6.0) evaluated outcomes for ex/gymnasts versus non-gymnasts; a slope/intercept discontinuity evaluated de-training effects.

Results—Data from 14 non-gymnasts and six ex/gymnasts represented outcomes from 4 years pre-menarche to 9 years post-menarche. All adjusted distal radius parameters were higher in ex/gymnasts than non-gymnasts ($p < 0.02$). Ulnar BMC, ulnar aBMD, and 1/3 aBMD temporarily decreased with gymnastic cessation ($p < 0.04$); ulnar area, 1/3 area, and 1/3 BMC did not change significantly. Skull outcomes did not differ between groups or change with activity cessation.

Conclusion—Gymnastic exposure during childhood and early puberty is associated with greater radius bone mass, size, and aBMD. Despite brief de-training losses in density and mass, significant skeletal benefits are manifested throughout growth and at least 4 years beyond activity cessation into early adulthood.

Keywords

Adolescence; Bone; DXA; Female; Mechanical loading; Radius

Introduction

Adult bone quality is likely improved by optimization of skeletal growth through childhood and adolescence. Mechanical loading during growth appears to enhance bone accrual. However, most evidence of residual benefits in adulthood is retrospective and cross-sectional in nature, based upon a single adult measurement only. There are few prospective, longitudinal studies that evaluate long-term benefits of pediatric loading in a series of observations as growth progresses. In a unique longitudinal study, Gunter et al. noted retention of skeletal improvements in a group of young women for 7 years after a childhood jumping program [1]. Benefits were small but significant (+1.4%) and had diminished since intervention completion.

Gymnastics has been studied extensively as a model of mechanical loading. Numerous pediatric studies have reported advantages in skeletal measures for gymnasts versus non-gymnasts, and several have reported increased bone accrual over a 1–3-year period. Several dual energy X-ray absorptiometry (DXA) studies report residual advantages in bone mineral measures among ex-gymnasts compared to non-gymnasts [2–5]. Complementing existing DXA evidence, Eser et al. used three-dimensional peripheral quantitative computed tomography (pQCT) to evaluate retention of skeletal advantages in ex-gymnasts (aged 18–36 years), 3–18 years after gymnastics cessation, reporting significant residual advantages in upper extremity bone geometry [6].

To date, there are no prospectively measured, longitudinal analyses documenting subject-specific acquisition of skeletal benefits during the course of childhood mechanical loading and demonstrating retention of these benefits in adulthood. Furthermore, most existing studies do not account for disparate rates of physical maturation among gymnasts and non-gymnasts, which may confound studies of skeletal development. Therefore, the purpose of this paper is to report preliminary results from a prospective, longitudinal study, accounting for variability in growth and maturation, and testing the hypothesis that skeletal benefits attributed to childhood gymnastic exposure persist into young adulthood.

Methods

Protocol for this longitudinal bone accrual study (1997–present) was approved by the SUNY Upstate Medical University Institutional Review Board and has been performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. Girls and/or their parents provided informed assent/consent, as dictated by subject age. Pre-menarcheal girls aged 8 to 12 were recruited in two phases (1997: 55 gymnasts, 20 non-gymnasts; 2002: 15 gymnasts, 25 non-gymnasts); a small subset of post-menarcheal gymnasts was recruited to compensate for peri-menarcheal subject attrition. As subjects were originally recruited for only 18–36-month studies, many withdrew after providing data for these periods. Of those who continued participation, few were included in this analysis due to stringent inclusion criteria: (1) achievement of gynecological age (years post-menarche) greater than 4 years; (2) for gymnasts, at least 2 years of pre-menarcheal gymnastic training (defined as greater than 6 h/week), continuing to 0.5 year pre-menarche and ceasing by 1 year post-menarche. Thus, “ex/gymnasts” were gymnasts prior to menarche and ex-gymnasts for at least 4 years post-menarche. Gymnasts who continued training beyond 1 year post-menarche were

excluded. “Non-gymnasts” were a heterogeneous group of athletes and non-athletes (e.g., lacrosse, basketball, track, dance).

Semi-annually, girls underwent anthropometric measurements and completed questionnaires on calcium intake, physical activity, and maturation [7]. Non-dominant forearm and total body DXA scans were performed annually. Total body scans measured total fat-free mass (FFM) and skull outcomes (areal bone mineral density (aBMD), bone mineral content (BMC)). Forearm scans were evaluated at ultradistal (metaphyseal) and 1/3 (diaphyseal) radius sites, yielding bone projected area, BMC, and aBMD (Hologic QDR 4500W). The coefficient of variation for this machine is 1% for both total body and forearm scans. The majority of scans were performed by the same technician (C. Riley, 2000 onward). All scans were re-analyzed by a single researcher (J. Dowthwaite) using Discovery A software (v12.7) to ensure optimal consistency. In contrast to standard Hologic protocols, forearm analysis boxes were placed to yield consistent distal radius regions of interest throughout development (ulnar position was disregarded due to discrepant ulna versus radius positions). The analysis box included the distal articular edge of the ulnar side of the radius and excluded carpal bones. The rationale for evaluation of non-dominant distal radius scans was: (1) total body mass impact loading of the non-dominant arm distinguishes gymnastic loading from most other activities, theoretically yielding the most sensitive indicator of adaptation to gymnastic exposure; (2) the radius is the primary weight-bearing bone in the distal forearm; and (3) influence of fan beam magnification error is minimal at this site. For comparison, the skull was evaluated as a non-loaded, control site.

Hierarchical linear modeling (HLM, also known as multilevel modeling) is a more complex outgrowth of traditional regression modeling used to link each subject’s repeated measures for appropriate treatment of longitudinal data with time-varying covariates (HLM v6.0, alpha=0.05). Menarcheal age and linear/quadratic functions of gynecological age (years pre- and post-menarche) were included in the model, centering analyses at menarche to account for the potential confounding influence of variability in rate of physical maturation upon bone outcomes. Height, FFM, and calcium intake served as time-varying covariates. Gymnastic status was evaluated dichotomously as the focus of this simple preliminary analysis; other weight-bearing physical activity was not evaluated. Intercept and slope discontinuities were evaluated as indicators of short- and long- term detriments associated with training cessation. Age at menarche was evaluated as a non-time-varying predictor. A priori power analyses used cross-sectional ANCOVA to compare forearm aBMD in ex-gymnasts versus non-gymnasts at 18 months post-menarche and >2 years post-cessation [5], yielding projected required cell sizes of $n=7$ (80% power). For this preliminary analysis, ex-gymnasts ($n=6$) are just short of estimated cell size for cross-sectional analyses, but post hoc power analyses for longitudinal HLM of all radius variables indicate >85% power to detect significant differences [8]. In contrast, for skull outcome differences, power was <10% due to smaller effect sizes.

Results

Distal radius parameters were evaluated for 20 subjects (14 non-gymnasts, 6 ex/gymnasts), representing growth from 4.0 years pre-menarche to 9.3 years post-menarche, totaling 146 observations (104 non-gymnast, 42 ex/gymnast). The number of annual DXA scans per subject varied from 4 to 11 (non-gymnasts 4–11 scans, mean=7.4; ex/gymnasts 6–8 scans, mean=7.0). There were no significant differences between groups for any independent variable at initial or final measurement points (Table 1, ANOVA, $p>0.05$); initial and final Tanner breast stage distributions were similar. Subsequent to menarche (non-gymnasts) or cessation of gymnastics (ex/gymnasts), ex-gymnast versus non-gymnast differences were not detected for physical activity participation (ANOVA, $p>0.64$).

Accounting for gynecological age, height, FFM, age at menarche, and calcium intake, all distal radius parameters were higher in ex/gymnasts than non-gymnasts ($p < 0.02$, Fig. 1a, b), as indicated by distinct ex/gymnast versus non-gymnast growth curves, in which points seldom overlap. In contrast, skull aBMD was not associated with gymnastic status ($p > 0.83$, Fig. 1c); ex/gymnast and non-gymnast curves are continuously intermingled and cannot be distinguished from each other. Similarly, skull BMC differences were not detected ($p > 0.98$, Fig. 1c), although there was a trend toward decreasing ex/gymnast BMC after gymnastic cessation ($p < 0.06$). Gymnastic cessation was not associated with a significant slope decrease for any radius outcome. However, gymnastic cessation was associated with an abrupt, temporary decrease in 1/3 aBMD, ultradistal BMC, and ultradistal aBMD (significant intercept discontinuity, $p < 0.04$). No significant gymnastic cessation effects were observed for 1/3 BMC, 1/3 area, ultradistal area, or skull aBMD. Age at menarche was not a significant predictor for any bone outcome ($p > 0.35$). Similarly, calcium intake was not a significant predictor, except for 1/3 aBMD (negative, $p < 0.04$).

Discussion

This longitudinal analysis provides the first preliminary evidence of prolonged, post-menarcheal retention of skeletal benefits attributed to mechanical loading during childhood and early adolescence. Ex-gymnasts demonstrated advantages in diaphyseal and metaphyseal distal radius aBMD, BMC, and projected area throughout growth and early adulthood, despite cessation of sub-elite gymnastics training around menarche. As such, ex-gymnast advantages were demonstrated prospectively into early adulthood, from 4 to 9 years post-menarche.

One other group has provided prospective, longitudinal evidence of skeletal benefit retention following childhood activity [1, 9, 10]. Fuchs et al. reported retention of benefits in a group of pre-pubertal children who had participated in a 7-month randomized, controlled high-impact loading intervention [9]. Advantages in total hip BMC for the intervention group were 5.4% at the completion of the intervention and 3.5% 7 months later. In a 7-year follow-up, jumpers maintained a significant 1.4% advantage in total hip BMC [1]. An identical intervention in a separate cohort yielded significantly greater BMC at the total body (2.9%), lumbar spine (2.3%), femoral neck (4.4%), and total hip (3.2%), 3 years following the intervention [10]. The authors attributed the gradual dissipation of benefits in the 7-year cohort to interactions between growth, physical activity, diet, and genetic predisposition over the subsequent period of extensive growth, thereby overwhelming effects of the brief intervention [1].

Long-term retention of childhood skeletal advantages has been suggested by several retrospective studies evaluating adult ex-gymnasts. In a cross-sectional evaluation, Bass et al. identified 6–26% advantages in aBMD at the arm, proximal femur, and lumbar spine for adult ex-gymnasts at 8 years post-cessation, compared to non-gymnasts; advantages were not diminished with increased cessation interval. Zanker et al. reported 10–17% aBMD advantages at the proximal femur, lumbar spine, and total body for adult ex-gymnasts 17 years post-cessation [11]. Similarly, at 15 years post-cessation, Kirchner et al. identified significant advantages in lumbar spine, proximal femur, and total body aBMD for former collegiate gymnasts compared to non-gymnasts [3]. At a follow-up evaluation 9 years later, these ex-gymnasts maintained 8–14% advantages over non-gymnasts, at multiple sites (lumbar spine, proximal femur, femoral neck, leg, and arm) and the total body, at a mean of 24 years post-cessation [12]. Ex-gymnasts in these adult studies had participated in gymnastics throughout childhood and adolescence; thus, results indicate maintenance of benefits when gymnastics is continued after completion of skeletal growth. Our maturity-

specific results suggest maintenance of skeletal benefits in early adulthood following loading exposure during childhood and early adolescence alone.

Eser et al. used three-dimensional pQCT to evaluate retention of skeletal advantages in a broad age range of ex-gymnasts who had ceased gymnastic participation 3–18 years (mean 6.1 years) prior [6]. These investigators identified ex-gymnast advantages in bone geometry of 20–32% in the upper extremity (humerus, radius). Of note, 20 subjects had been retired for 3–6 years, and ten subjects had been retired for 6–18 years. Ex-gymnasts were 18–36 years old (mean age 23 ± 0.9 years) at the time of pQCT study, had participated in gymnastics from a mean age of 6.1 years (range 3.0–9.6 years) and had trained for an average of 10.5 years (range 6–16 years). With a mean menarcheal age of 14.7 years, it appears that most, if not all, ex-gymnasts trained into their early post-menarcheal years. This contrasts with our population of ex/gymnasts; only one girl participated in gymnastics for more than 1 month post-menarche, retiring at 1 year post-menarche. In addition, the ex-gymnasts in the study by Eser et al. participated at a higher intensity than the ex/gymnasts in our study, with a highest level of 40 h/week and average peak at 23 h/week [6]. The highest annual mean for our cohort was 18.8 h/week, with an average peak annual mean of 14.3 h/week (the average annual mean for the year prior to cessation was 14.2 h/week). Thus, compared to ex-gymnasts in the study by Eser et al., our results reflect relatively conservative gymnastic exposure. Furthermore, our ex/gymnasts and non-gymnasts did not differ significantly for anthropometric measures at either the initial or the final measurement point, indicating that our ex/gymnasts were effectively “normal girls” exposed to gymnastic loading during growth.

Geometric adaptations appear to contribute to observed aBMD advantages in our ex-gymnast cohort, as indicated by significant advantages in radius projected area. Previously, in larger, related samples, we have associated enlarged bone geometry with gymnastic loading using DXA [13] and pQCT [14]. Further evidence of geometric adaptation is provided by childhood gymnast pQCT studies [15, 16] and ex-gymnast results by Eser et al. [6]. Corroborating Eser et al., our results suggest that geometric adaptation to childhood and early adolescent loading persists into adulthood, 4 to 9 years after activity cessation.

In a cross-sectional study of pre-pubertal girls, Courteix et al. reported a deficit in skull BMC for gymnasts relative to swimmers and non-gymnasts [17]. These authors suggested that the skull may be drained of BMC to supplement mineralization at loaded sites [2]. In our longitudinal data, such a phenomenon would be expected to appear as low gymnast BMC/aBMD during pre-menarcheal loading, with a rebound increase in skull aBMD or BMC after training cessation. We detected no significant skull BMC/aBMD activity group difference, with a contradictory trend toward *decreasing* gymnast skull BMC after gymnastic cessation ($p < 0.06$), possibly reflecting a systemic bone metabolic shift. Our results corroborate those of Bass et al., who detected no difference in skull aBMD between pre-pubertal gymnasts and non-gymnasts, despite significant gymnast advantages at loaded sites [2]. We interpret all of the above as evidence for the role of mechanical loading in observed ex/gymnast advantages, weakening the argument that gymnast advantages are attributable to self-selection for robust bone.

Limitations

Although skull outcomes are subject to positional variation in pediatric subjects, this problem was likely alleviated by large numbers of repeated observations per subject. Because this study is not a randomized, controlled intervention, ex-gymnast skeletal benefits are correlational in nature. Further-more, ex-gymnast pre-exposure skeletal parameters are unknown, as subjects had been training for 2 to 8 years prior to the initial DXA scan.

Although statistical power is bolstered by large numbers of repeated observations, subject numbers are small. In particular, due to the stringent inclusion criteria for maturation-specific timing of gymnastic exposure, few ex-gymnasts are represented. Our capacity to evaluate retention of benefits beyond 4 years post-menarche is limited by our relatively young cohort. Continued observation of our entire cohort will enhance power (more subjects) and provide a longer period to assess benefit retention (more data points beyond 4 years post-menarche), enabling future analyses of skeletal sites with lower theoretical loading contrasts and higher required sample sizes (e.g., hip, lumbar spine).

Conclusion

Gymnastic exposure during childhood and early puberty is associated with enhanced radius bone mass, size, and areal density. Despite evidence of brief de-training losses in density and mass, significant benefits appear to persist for at least 4 years beyond activity cessation and into early adulthood, corroborating results from previous retrospective studies.

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Fig. 1.

Ex/gymnast and non-gymnast data are depicted over a 12-year period of longitudinal growth/accrual, aligned by physical maturity. Data points are aligned by years since menarche (gynecological age) and adjusted for age at menarche, as well as time-varying height, DXA fat-free mass, and calcium intake (ex-gymnasts=large, red subject-specific shapes; non-gymnasts=small, blue subject-specific shapes). Distal radius bone mineral content, areal bone mineral density, and projected area for 1/3 (a) and ultradistal (b) radius sites and skull areal bone mineral density (c) are presented. Gymnastic cessation occurred between gynecological age -0.5 to 1.0 years, as represented by vertical lines. The most notable gymnastic cessation “effects” are visible for 1/3 aBMD ($p < 0.05$, a), UDBMC and UDBMD ($p < 0.05$, b)

Table 1

Subject characteristics by gymnast status

Variable	Ex/Gymnasts (n=6)			Non-gymnasts (n=14)		
	Min to Max	Initial	Final	Min to Max	Initial	Final
Gynecological Age (years)	-3.5 to +9.4	-1.7 (2.5)	+7.0 (2.2)	-4.0 to +9.3	-1.6 (1.4)	+6.2 (1.8)
Chronological Age (years)	9.1 to 22.6	11.3 (2.1)	20.0 (2.1)	9.8 to 22.0	11.0 (1.3)	18.9 (1.9)
Age at Menarche (years)	12.1 to 13.7	Mean=13.1 (0.6)		11.2 to 13.9	Mean=12.7 (0.9)	
Tanner Breast Stage	1 to 5	TI=2; TII=3; TV=1	TI=1; TIV=1; TV=4	1 to 5	TI=2; TII=10; TIII=1; TIV=1	TIII=1; TIV=2; TV=11
Height (m)	1.32 to 1.73	1.43 (0.10)	1.66 (0.05)	1.33 to 1.76	1.44 (0.07)	1.65 (0.04)
Weight (kg)	28.4 to 78.0	36.1 (7.7)	62.5 (9.2)	28.9 to 69.2	36.6 (6.8)	58.7 (6.1)
FFM (kg)	21.7 to 45.8	27.4 (6.1)	41.9 (2.1)	20.5 to 46.5	26.4 (5.0)	39.6 (3.3)
Percent Body Fat (%)	16.8 to 38.4	20.2 (2.3)	27.6 (8.6)	16.4 to 34.1	24.3 (5.4)	27.5 (5.0)
Gymnastics (h/week)	0 to 18.8	9.3 (4.7)	-	-	-	-
Post-men/Post-Quit Activity (h/week)	0 to 10.3	Mean=5.25 (3.0)		0.3 to 5.9	Mean=4.6 (2.2)	
Calcium Intake (mg/day)	182.1 to 1710.5	746.8 (379.5)	612.3 (192.0)	101.7 to 1572.6	860.8 (377.7)	799.6 (350.2)
Mean Calcium (mg/day)	352.5 to 1274.8	Mean=778.4 (341.7)		292.9 to 1163.1	Mean=814.5 (253.1)	

Group minima and maxima are presented for the study period. For initial and final data points, group means (standard deviations) or frequencies (Tanner breast stage) are presented. Aside from gymnastic exposure, which differed by design, there were no significant differences between groups for any variable.

FFM DXA-measured total body non-bone lean mass, *Post-men/Post-quit Activity* mean h/week physical activity since menarche (non-gymnasts) or gymnastic cessation (ex-gymnasts).