Muscle Function, Dynamic Loading, and Femoral Neck Structure in Pediatric Females

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[1]Department of Orthopedic Surgery, SUNY Upstate Medical University, Syracuse, NY; [2]Department of Exercise Science, Syracuse University, Syracuse, NY; [3]Department of Public Health and Preventive Medicine, SUNY Upstate Medical University, Syracuse, NY; [4]Vitality Program, College of Health Professions, SUNY Upstate Medical University, Syracuse, NY; and [5]Department of Orthopedics and Rehabilitation, University of Wisconsin, Madison, WI

ABSTRACT

DOWTHWAITE, J. N., P. F. ROSENBAUM, C. A. SAMES, and T. A. SCERPELLA. Muscle Function, Dynamic Loading, and Femoral Neck Structure in Pediatric Females. *Med. Sci. Sports Exerc.*, Vol. 46, No. 5, pp. 911–919, 2014. **Purpose**: Muscle forces influence the development of bone mass and structure, but dynamic loading via impact exercise is considered particularly osteogenic. We hypothesized that indices of local muscle function and physical activity exposure would predict femoral neck (FN) structure in premenarcheal females. **Methods**: We tested this hypothesis in 76 healthy, premenarcheal girls (46 gymnasts and 30 nongymnasts). Height, weight, Tanner breast stage, and prior year nonaquatic, organized physical activity level (PAL) were recorded semiannually. Hologic dual-energy x-ray absorptiometry scans (whole body, left FN) yielded total body nonbone lean mass and bone outcomes, including narrow neck (NN) hip structural analysis data. Dynamometers assessed nondominant hand grip and left hip flexion/extension indices. Parsimonious regression models tested the following as predictors of bone outcomes: local muscle function, PAL, gymnast status, and lean mass, accounting for Tanner breast stage and height, as appropriate. **Results**: Hip flexion indices were significantly correlated with indices of FN mass, density, structure, and strength ($P < 0.05$). However, the entry of PAL, gymnast status, and lean mass into regression models supplanted local muscle function explanatory value. In contrast, for many variables, the significant association of gymnast status persisted after accounting for physical maturity, body size/lean mass, and PAL. For all skeletal indices except FN_{Area}, NN_{width}, NN endosteal diameter, and NN buckling ratio, gymnast status was more strongly associated with bone outcomes than PAL. **Conclusions**: Greater activity doses and exposure to extreme dynamic loading provide independent benefits to FN structure during growth. Furthermore, weight-bearing activity and high-impact exercise exposure appear superior to local muscle force measures for prediction of FN structure. **Key Words:** HSA, PREMENARCHE, BIODEX, DXA, PHYSICAL ACTIVITY

Evidence suggests that mechanical loading via physical activity during growth may be a potent strategy for maximizing peak bone mass, improving bone strength and reducing lifetime fracture risk (2,7,11,12,17,26,27). Many investigators consider muscular forces to be paramount in exercise-related bone stimulation and subsequent advantages in skeletal strength. The mechanostat theory postulates a direct cause-and-effect relationship between muscular forces and bone structure under normal conditions (22,23,28,29). Because muscular force is strongly positively correlated with muscle mass and cross-sectional area (CSA), these anatomic parameters have been used as proxies for muscle force (22,25,29,37). In turn, positive associations between these muscle force proxies and bone outcomes are often cited to support the concept that increasing muscle mass (and therefore force generation capacity) provides the stimulus to increase bone mass and strength (22,28,29).

Judex and Rubin (15) describe two muscle-mediated osteogenic pathways: 1) muscle generates osteogenic forces during resistance to external stimuli, and 2) external stimuli produce muscle hypertrophy, secondarily augmenting muscular osteogenic potential via capacity to generate greater muscular force. In addition, in the context of weight-bearing and impact exercise, muscle hypertrophy may yield greater body mass to be borne, increasing the "mass" component of external mechanical forces.

Impact exercise may be viewed as a special type of dynamic mechanical loading, as it generates rapid application of skeletal loads via three main routes: 1) concentric muscular contractions (propulsion), 2) eccentric muscular contractions (load dampening), and 3) "direct" loading at contact and articular surfaces (during both takeoff and landing). Judex and Rubin have described "direct" osteogenic forces as "reactionary forces produced by the skeleton with a substrate (e.g., ground reaction forces)" and as "mechanical force (acceleration) traveling from the interface … to a given anatomical site" (15). In the case of the femur, "direct" skeletal

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loading is applied at both distal and proximal articular surfaces, elevating osteoarthritis risk in athletes exposed to high impact loads and high training volumes (14). In numerous animal models, "direct" loading has yielded osteogenesis, isolated from muscular forces (13,24,33,35), demonstrating that skeletal adaptation to mechanical force may be stimulated without muscle mediation.

In human subjects, artistic gymnastic maneuvers have been shown to generate extreme ground reaction forces (4), which are often imposed at high training volumes. Thus, gymnastics may be considered an extreme form of dynamic loading that is likely to exaggerate both "direct" and muscle-mediated loading. In a recent study, we evaluated associations between extreme dynamic loading, muscle CSA, and radius skeletal structure using the human model of gymnastic loading in a group of postmenarcheal girls (9). In that analysis, prior gymnastic exposure was a significant predictor of upper extremity indices of bone mass, geometry, and strength, independent of local indices of muscle mass and CSA (9). These results suggest that exposure to "direct" forces applied via gymnastic loading may provide a stimulus for skeletal adaptation independent from muscular force.

We hypothesized that both increased exposure to dynamic loading and capacity to generate local muscular forces would be significant, independent predictors of bone mass, structure, and theoretical strength at the proximal femur in young girls. To test this hypothesis, we evaluated physical activity dose and indices of muscular function as predictors of femoral neck (FN) structure in a group of premenarcheal gymnasts and nongymnasts, accounting for physical maturity and body size/lean mass. If exposure to extreme dynamic loading (gymnastics) predicts FN structure, independent of local muscular forces, these results would support the concept that bone adaptation is not modulated by muscular forces alone.

METHODS

In accordance with the Declaration of Helsinki, and after the approval of study protocols by the institutional review board of SUNY Upstate Medical University, 80 girls provided informed assent with parental consent to participate in a longitudinal study of bone growth in relation to physical activity. Subjects were healthy girls, ages 8 to 15 yr, free of bone disease. Nongymnasts were recruited from the local community, representing heterogeneous physical activity participation. Gymnasts were recruited from gymnastic training centers in upstate New York. To account for even minimal or sporadic exposure to gymnastic loading, subjects with at least 1 $h{\cdot}wk^{-1}$ annual mean gymnastic exposure for the year before the index dual-energy x-ray absorptiometry (DXA) scan were categorized as gymnasts (GYM); those with <1 $h{\cdot}wk^{-1}$ were classified as nongymnasts (NON). In this manner, gymnastic status was used as a marker for exposure to extreme dynamic loading, whereas general physical activity level (PAL) was used to sum and quantify all forms of mechanical loading via organized nonaquatic physical activity (as described in the following paragraphs). Postmenarcheal girls were excluded from the current analyses.

Age was calculated to the nearest tenth of a year, subtracting the date of birth from the date of DXA. Height (m) was measured using a stadiometer; weight (kg) was measured in light clothing with an electronic scale (Detecto, Webb City, MO). With parental assistance, subjects used annotated line drawings to determine self-assessed Tanner breast stage; menarche status was also recorded. Organized physical activity participation for the preceding year was reported by subjects with assistance from their parent(s); prior comparisons between gymnasts' training records and coaches logs indicated reliable reporting, $r > 0.97$ ($P < 0.001$) (10). These data were used to generate PAL scores, defined as mean hours per week participation in organized, nonaquatic physical activity, including gymnastics.

Indices of muscular function were measured using dynamometers. Maximum nondominant hand grip strength was assessed from three trials (GR, kg; Takei, Nigata, Japan). Indices of left hip flexion and extension function were measured on a Biodex System 3 isokinetic dynamometer (Biodex, Shirley, NY) by the same two investigators (CS and KK). The Biodex was calibrated before each testing session, per manufacturer recommendations (3). Attachments were chosen based on hip width and femur length to ensure proper alignment and to secure positioning on the thigh support; pediatric hip attachments were used for children with narrow thighs and/or short femurs.

Hip flexion and extension testing occurred in a supine position, with the seat back fully reclined and the attachment shaft aligned with the axis of rotation, per the Biodex operation manual (3). To minimize upper body movement, two cross-chest shoulder straps were used, and subjects were instructed to cross their arms across their chest. The velocity of the hip flexion and extension testing was set at $60^{\circ}{\cdot}s^{-1}$, in the isokinetic concentric/concentric mode. Before testing, each subject was given both verbal and visual instructions and performed three submaximal repetitions for familiarization with the protocol. After 1 min of rest, each subject was instructed to perform three maximal repetitions with instructions to move the dynamometer lever arm "as hard and as fast as possible"; after 1 min of rest, the maximal protocol was repeated to yield two sets of maximal data. The coefficient of variation (CV) was evaluated to ensure that for at least one set, all three repetitions differed by no more than 15%. If the CV exceeded 15% for both sets, the subject was given a 5-min rest before repeating the test; during this rest, instructions were reviewed, and the axis of rotation and the proper stabilization were checked. The data with the lowest CV (15% or lower) were included in the present analyses. All dynamic torque data were filtered, windowed, and gravity corrected. Biodex outcomes included indices of hip flexion and extension function as follows: peak torque (N·m), peak torque for body weight (%), maximum total work (J), total work (J), and average power (W). For Biodex variables, total group mean percent CV were 12.6% (hip flexion) and 10%

(hip extension); by gymnastic exposure subgroup, mean CV were as follows: GYM hip flexion = 11.0%, GYM hip extension = 8.7%; NON hip flexion = 14.1%, NON hip extension = 11.9%.

DXA scans were performed for the whole body and left proximal femur by one of two certified DXA technologists and analyzed by a single, trained investigator (JND) (Hologic Discovery A, software version 12.7.3.2:3). Whole-body DXA scans yielded total body nonbone lean mass (tb_{FFM}, kg) and left leg nonbone lean mass (leg_{FFM}, kg). Left proximal femur DXA scans yielded FN and femoral narrow neck (NN) bone outcomes. For simplicity, both FN and NN outcomes are referred to in the text as "femoral neck" outcomes, with individual variables labeled as FN or NN, as appropriate. Dependent variables included FN projected area (FN_{Area}, cm), bone mineral content (FN_{BMC}, g), and areal bone mineral density (FN_{aBMD}, $g{\cdot}cm^{-2}$), as well as hip structural analysis output (HSA) for femoral NN bone geometry and theoretical strength. For the femoral NN, HSA yields total bone tissue CSA (NN_{bCSA}, cm^2), cross-sectional moment of inertia (NN_{CSMI}, cm^4), NN periosteal width (NN_{width}, cm), endosteal diameter (NN_{ED}, cm), cortical thickness (NN_{CT}, cm), section modulus (NN_Z, cm^3), and buckling ratio (NN_{BR}). Buckling ratio is a composite variable, derived as maximum distance from the bending plane centroid (a function of periosteal width) divided by cortical thickness (16). Accordingly, it is important to note that NN_{BR} results demonstrate patterns that contrast with most of the other FN outcomes, as low NN_{BR} values indicate lower fracture risk (greater bone strength) and high values indicate higher fracture risk (lower bone strength).

The CV in our laboratory were calculated using duplicate scans of middle-age females. For the total body scans, 29 scan pairs yielded CV for lean mass and left leg lean mass of 0.5% and 1.1%. For the FN, 32 scan pairs yielded CV <3.5% for all variables except NN buckling ratio (4.1%), NN section modulus (7.2%), and NN cross-sectional moment of inertia (9.3%). Aside from NN_Z and NN_{CSMI}, these CV are lower than or within 0.6% of those reported by other research groups using FN and HSA data (16,20).

Data were evaluated for normality of distribution. Most continuous variables were natural log (ln) normal and, therefore, were transformed before analysis; PAL scores were less normally distributed in natural log form, so they were analyzed without transformation. Preliminary analyses included the calculation of descriptive statistics for the total sample and with stratification by gymnastic exposure status (GYM/NON), including assessment of possible gym status differences using analysis of variance (ANOVA). Correlations were performed to assess linear relationships and collinearity among independent variables (ln_{age}, ln_{height}, ln_{tbFFM}, ln_{legFFM}, ln_{GR}), Biodex variables (ln and PAL) and dependent variables ($lnFN_{BMC}$, $lnFN_{aBMD}$, $lnNN_{bCSA}$, $lnNN_{CT}$, $lnNN_{CSMI}$, $lnNN_Z$, and $lnNN_{BR}$).

Regression models were developed based on the results of the correlations. Specifically, for local muscular strength predictors, the variable with the highest correlation coefficient was entered; this was hip flexion peak torque (HFPT) for all variables except NN_{BR}, for which hip flexion maximum total work (HFMTW) was entered. Age and weight were not entered because of inferior explanatory value and strong collinearity with height and lean mass (age, $r > 0.75$, 0.73; weight, $r = 0.87$, 0.96, respectively). Moreover, height and lean mass were most appropriate for hypothesis testing. To account for the effects of physical maturity and body size, Tanner breast stage and height were entered before evaluating the statistical effects of the following, in succession: 1) local muscular strength index, 2) organized physical activity exposure during the prior year, and 3) exposure to extreme dynamic loading (gymnast status: GYM or NON). Finally, the full model was reevaluated, substituting total body lean mass (tb_{FFM}) for height; substantial collinearity precluded simultaneous inclusion of height and tb_{FFM} in the final model (variance inflation factors > 7). We used this final model to evaluate whether skeletal muscle mass encapsulated the effects of local muscle strength, activity dose, and exposure to extreme dynamic loading. Adjusted model r^2, unstandardized beta coefficients, 95% confidence intervals, and significance levels are reported in tabular form. Significance was defined as $\alpha < 0.05$.

This pilot analysis of muscle–bone relationships uses data from a longitudinal study of bone accrual in relation to gymnastic loading exposure. Sample size was originally determined to detect significant FN_{aBMD} differences for GYM versus NON with >80% power after at least 5 yr of study (required cell sizes, $n = 17$). GYM were oversampled to allow for potential training cessation; all subjects were oversampled to allow for 5-yr subject attrition. Although no literature was available to power analyses concerning hip flexion indices versus hip structural analysis outcomes in GYM and NON, our sample (NON $n = 30$ and GYM $n = 46$) nearly doubles that of a study that detected significant FN_{aBMD} differences between adult NON ($n = 22$) and GYM ($n = 18$)(32).

RESULTS

Subjects. Of 84 subjects originally recruited, 4 girls were excluded from analysis because of postmenarcheal status, and 4 girls were excluded because of incomplete data, yielding 76 premenarcheal girls with complete data for all bone and muscle parameters at the time of analysis (46 GYM and 30 NON). Subject characteristics are presented in Table 1 (TOTAL, NON, and GYM). No significant differences were detected by ANOVA for any variable reported, except that GYM mean values were greater than NON mean values for FN_{aBMD}, annual mean PAL, and gymnastic training hours ($P < 0.05$); group mean percent body fat was higher for NON than GYM ($P < 0.05$). Tanner breast stage distributions did not differ by activity group (χ^2 $P > 0.05$); overall, 59% of subjects reported Tanner breast stage as TI, 32%

TABLE 1. Subject characteristics.

	Total Sample (n = 76)				Nongymnasts (NON, n = 30)				Gymnasts (GYM, n = 46)			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Chronological age (yr)	10.5	1.6	7.8	14.3	10.3	1.5	7.8	13.6	10.6	1.7	8.1	14.3
Height (cm)	139.9	11.1	117.0	163.0	142.1	10.2	125.0	161.0	138.4	11.6	117.0	163.0
Weight (kg)	35.6	10.5	22.6	72.2	37.3	11.6	24.4	72.2	34.4	9.6	22.6	62.4
BMI ($kg \cdot m^{-2}$)	17.8	2.9	13.5	28.0	18.2	3.7	13.5	28.0	17.6	2.3	14.2	24.4
DXA body fat (%)	23.3	6.0	13.6	40.3	26.4[a]	6.9	14.2	40.3	21.3	4.4	13.6	35.2
DXA tb_{FFM} (kg)	25.9	6.4	16.7	42.6	25.8	5.9	18.2	41.7	25.9	6.8	16.7	42.6
DXA leg_{FFM} (kg)	4.2	1.2	2.5	7.5	4.2	1.2	2.5	7.5	4.2	1.2	2.5	7.5
PAL ($h \cdot wk^{-1}$)	8.3	5.5	0.2	25.0	3.8	2.6	0.2	12.1	11.2[a]	4.9	1.3	25.0
Gymnastic exposure ($h \cdot wk^{-1}$)	6.0	6.3	0.0	25.0	0.0	0.2	0.0	0.8	10.0[a]	5.2	1.1	25.0
Grip strength (kg)	15.9	4.7	7.0	32.0	16.1	4.6	7	25	15.8	4.7	8	32
HFPT ($N \cdot m$)	27.3	13.0	7.8	66.3	25.5	12.9	9.6	66.3	28.5	13.0	7.8	65.5
HFMTW (W)	18.4	9.2	3.6	39.0	16.7	8.1	4.7	37.7	19.5	9.8	3.6	39.0
DXA FN area (cm^2)	3.95	0.43	2.97	5.18	4.00	0.46	2.97	5.18	3.92	0.40	3.19	4.86
DXA FN_{BMC} (g)	2.81	0.65	1.54	4.82	2.66	0.64	1.54	4.65	2.90	0.64	2.14	4.82
DXA FN_{aBMD} ($g \cdot cm^{-2}$)	0.706	0.105	0.461	0.990	0.660	0.094	0.461	0.937	0.735[a]	0.101	0.592	0.990

[a] Greater group mean, $P \leq 0.001$.

BMI, body mass index; tb_{FFM}, total body nonbone lean mass; HFMTW, hip flexion maximum repetition total work; leg_{FFM}, nonbone, left leg lean mass; FN, femoral neck.

reported TII, and 9% reported TIII (NON: 57% TI, 37% TII, 7% TIII; GYM: 61% TI, 28% TII, 11% TIII).

Correlations. Pearson correlation coefficients for independent variables versus FN bone outcomes are presented in Table 2 for all subjects. Height, lean mass (tb_{FFM}), and left leg lean mass (leg_{FFM}) demonstrated moderate to high correlations with most bone outcomes, $P < 0.05$ ($r > 0.57$ for all but NN_{ED} and NN_{BR}, leg_{FFM} specifics not shown). For all bone outcomes except NN_{ED}, correlations with lean mass were stronger than correlations with height. Lean mass and leg lean mass were highly, positively correlated ($r = 0.99$, $P < 0.001$). Because total body lean mass correlations were slightly higher than those for leg lean mass for all bone outcomes except NN_{BR} ($r = -0.276$ and -0.283, respectively), total body lean mass was chosen as the lean mass variable for regression model entry. Both nondominant arm grip strength and HFPT showed moderate to high, significant correlations with most bone outcomes; the exception was HFPT with NN_{ED} and NN_{BR}. For NN endosteal diameter, the strongest hip strength correlate was HFMTW ($r = -0.23$, $P = 0.04$). In all cases, hip extension peak torque exhibited weaker correlations with bone outcomes (not shown). Grip strength correlated more strongly with all bone outcomes than any of the local hip muscle function indices. For the group as a whole, PAL showed moderate, significant correlations with FN_{BMC}, FN_{aBMD}, NN bone tissue CSA (NN_{bCSA}), NN cortical thickness, and NN buckling ratio.

Regression models. In the simplest height-based models, height was a significant predictor of all bone outcomes except cortical thickness (NN_{CT}) and buckling ratio (NN_{BR}) (Tables 3A and 3B). Tanner breast stage was significantly associated with FN_{BMC}, FN_{aBMD}, NN bone tissue CSA (NN_{bCSA}), NN_{CT}, and NN_{BR}. Height was the strongest predictor of all bone outcomes except FN_{aBMD}, NN_{CT}, and NN_{BR}, for which Tanner breast stage was the most potent predictor. After accounting for the effects of physical maturity and body size, hip flexion index was significantly positively correlated with only two bone outcomes: FN_{BMC} and NN section modulus (NN_Z), although there were trends for greater bone strength indices with stronger hip flexion for FN_{aBMD}, NN_{CT}, NN_{BR}, and NN_{CSMI} ($0.06 \leq P < 0.15$).

With the entry of PAL for the year prior into the regression models, hip flexion indices were no longer significant predictors of bone outcomes ($P > 0.08$). In contrast, height retained its significant associations with all bone outcomes except NN_{BR}. Tanner breast stage associations remained statistically significant for FN_{BMC}, FN_{aBMD}, NN_{bCSA}, NN_{CT}, and NN_{BR}. PAL was significantly associated with all bone

TABLE 2. Pearson correlation coefficients for bone outcomes and independent variables.

DXA FN and NN Outcomes	Tanner Breast Stage	ln Height	ln tb_{FFM}	PAL	ln Grip Strength	ln HFPT
$\ln FN_{BMC}$	0.69***	0.77***	0.87***	0.43***	0.74***	0.53***
$\ln FN_{Area}$	0.57***	0.75***	0.77***	$0.14_{(0.24)}$	0.70***	0.46***
$\ln FN_{aBMD}$	0.61***	0.59***	0.73***	0.54***	0.58***	0.45***
$\ln NN_{bCSA}$	0.63***	0.74***	0.84***	0.36***	0.65***	0.49***
$\ln NN_{CSMI}$	0.52***	0.72***	0.77***	$0.21_{(0.07)}$	0.61***	0.47***
$\ln NN_{width}$	0.33***	0.59***	0.59***	$-0.10_{(0.40)}$	0.45***	0.31**
$\ln NN_{ED}$	$0.20_{(0.08)}$	0.47***	0.45***	−0.23*	0.34**	$0.23_{(0.05)}$
$\ln NN_{CT}$	0.60***	0.55***	0.69***	0.56***	0.54***	0.42***
$\ln NN_Z$	0.55***	0.71***	0.79***	0.33**	0.63***	0.50***
$\ln NN_{BR}$[a]	−0.34*	$-0.15_{(0.20)}$	−0.28*	−0.60***	−0.23*	$-0.21_{(0.06)}$

*$P < 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$. All other P values are shown in parentheses.

[a] For NN_{BR}, hip flexion maximum repetition total work $r = -0.23$ ($P = 0.04$).

tb_{FFM}, total body lean mass; PAL, physical activity level; HFPT, hip flexion peak torque; bCSA, total bone tissue cross-sectional area; CSMI, cross-sectional moment of inertia; ED, endosteal diameter; CT, cortical thickness; Z, section modulus; BR, buckling ratio.

TABLE 3. Regression results.

FN Outcome	Model Adjusted r^2	β (95% CI)					
		Constant	Tanner Breast Stage	Height or tb$_{FFM}$	HFPT	PAL	GYM (Gymnast Status)
A. Height- and Lean Mass–Based Models for Left FN Bone Mass, Density, and Cortical Outcomes—Evaluating the Statistical Effects of Biodex Hip Strength, Habitual PAL, Gymnast Status, and Tanner Breast Stage							
FN$_{BMC}$	0.671***	−5.827*** (−8.136 to −3.518)	**0.105***** (0.050 to 0.161)	**1.302***** (0.812 to 1.792)	**0.078*** (0.012 to 0.144)	—	—
	0.730***	−5.981*** (−8.074 to −3.889)	**0.091***** (0.041 to 0.142)	**1.336***** (0.892 to 1.780)	0.054$^{(0.08)}$ (−0.007 to 0.114)	**0.010***** (0.005 to 0.015)	—
	0.750***	−6.933*** (−9.076 to −4.790)	**0.089***** (0.041 to 0.138)	**1.533***** (1.079 to 1.986)	0.046$^{(0.12)}$ (−0.013 to 0.105)	0.004 (−0.002 to 0.011)	**0.095*** (0.022 to 0.168)
	_0.806***_	_−6.071*** (−7.507 to −4.635)_	_0.042$^{(0.08)}$ (−0.005 to 0.089)_	_**tb$_{FFM}$ = 0.682***** (0.529 to 0.836)_	_0.012 (−0.041 to 0.066)_	_0.002 (−0.003 to 0.008)_	_**0.074*** (0.012 to 0.136)_
FN$_{aBMD}$	0.443***	−3.068** (−5.095 to −1.042)	**0.082***** (0.033 to 0.130)	**0.488*** (0.058 to 0.919)	0.055$^{(0.06)}$ (−0.003 to 0.112)	—	—
	0.589***	−3.231*** (−4.973 to −1.488)	**0.067**** (0.025 to 0.109)	**0.524**** (0.155 to 0.894)	0.029 (−0.021 to 0.080)	0.011*** (0.007 to 0.015)	—
	0.627***	−4.096*** (−5.863 to −2.329)	**0.065**** (0.025 to 0.105)	**0.703***** (0.329 to 1.077)	0.022 (−0.026 to 0.071)	0.005$^{(0.06)}$ (0.000 to 0.011)	**0.086**** (0.026 to 0.146)
	_0.681***_	_−4.078*** (−5.322 to −2.833)_	_0.035$^{(0.09)}$ (−0.006 to 0.076)_	_**tb$_{FFM}$ = 0.353***** (0.221 to 0.486)_	_0.001 (−0.046 to 0.047)_	_0.004$^{(0.11)}$ (−0.001 to 0.009)_	_**0.080**** (0.027 to 0.134)_
NN$_{bCSA}$	0.588***	−6.435*** (−9.002 to −3.867)	**0.084**** (0.022 to 0.145)	**1.356***** (0.811 to 1.901)	0.066$^{(0.08)}$ (−0.007 to 0.140)	—	—
	0.622***	−6.555*** (−9.019 to −4.091)	**0.072*** (0.013 to 0.132)	**1.383***** (0.860 to 1.906)	0.047 (−0.024 to 0.119)	**0.008**** (0.002 to 0.014)	—
	0.656***	−7.777*** (−10.277 to −5.277)	**0.070*** (0.013 to 0.127)	**1.635***** (1.107 to 2.164)	0.038 (−0.031 to 0.106)	0.000 (−0.007 to 0.008)	**0.122**** _(0.037 to 0.207)_
	_0.730***_	_−6.986*** (−8.671 to −5.301)_	_0.017 (−0.039 to 0.072)_	_**tb$_{FFM}$ = 0.742***** (0.562 to 0.922)_	_0.000 (−0.064 to 0.063)_	_−0.002 (−0.009 to 0.005)_	_**0.101***** (0.028 to 0.174)_
NN$_{CT}$	0.409***	−4.479*** (−6.929 to −2.030)	**0.103***** (0.044 to 0.161)	0.474$^{(0.07)}$ (−0.046 to 0.994)	0.059$^{(0.10)}$ (−0.011 to 0.129)	—	—
	0.581***	−4.685*** (−6.749 to −2.620)	**0.084***** (0.034 to 0.134)	**0.519*** (0.081 to 0.958)	0.027 (−0.033 to 0.087)	**0.014***** (0.009 to 0.018)	—
	0.622***	−5.739*** (−7.826 to −3.652)	**−0.082***** (0.034 to 0.129)	**0.737***** (0.296 to 1.179)	0.018 (−0.039 to 0.075)	**0.007*** (0.001 to 0.013)	**0.105**** (0.034 to 0.176)
	_0.655***_	_−5.550*** (−7.067 to −4.032)_	_**0.054*** (0.004 to 0.104)_	_**tb$_{FFM}$ = 0.352***** (0.190 to 0.514)_	_−0.002 (−0.058 to 0.055)_	_0.006$^{(0.06)}$ (0.000 to 0.012)_	_**0.097**** (0.032 to 0.163)_
NN$_{BR}$[a]	0.110***	−0.041 (−3.765 to 3.683)	**−0.120**** (−0.208 to −0.033)	**0.483** (−0.303 to 1.269)	−0.068$^{(0.13)}$ (−0.157 to 0.020)	—	—
	0.378***	0.464 (−2.654 to 3.583)	**−0.090*** (−0.164 to −0.016)	0.379 (−0.279 to 1.037)	−0.020 (−0.096 to 0.056)	**−0.021***** (−0.028 to −0.013)	—
	0.399***	1.490 (−1.770 to 4.750)	**−0.087*** (−0.160 to −0.015)	0.169 (−0.517 to 0.855)	−0.013 (−0.088 to 0.062)	**−0.014**** (−0.024 to −0.005)	−0.101$^{(0.07)}$ (−0.210 to 0.008)
	_0.398***_	_1.940$^{(0.12)}$ (−0.487 to 4.368)_	_**−0.085*** (−0.166 to −0.005)_	_tb$_{FFM}$ = 0.037 (−0.218 to 0.292)_	_−0.010 (−0.086 to 0.065)_	_**−0.014**** (−0.024 to −0.004)_	_**−0.107*** (−0.212 to −0.001)_
B. Height- and Lean Mass-based Models for Left Femoral NN HSA Bone Geometry and Strength Indices—Evaluating the Statistical Effects of Biodex Hip Strength, Habitual PAL, Gymnast Status, and Tanner Breast Stage							
FN$_{Area}$	0.575***	−2.758*** (−4.048 to −1.469)	0.024$^{(0.13)}$ (−0.007 to 0.055)	**0.813***** (0.540 to 1.087)	0.023 (−0.014 to 0.060)	—	—
	0.569***	−2.751*** (−4.049 to −1.452)	0.024$^{(0.12)}$ (−0.007 to 0.056)	**0.812***** (0.536 to 1.087)	0.024 (−0.013 to 0.062)	0.000 (−0.004 to 0.003)	—
	0.564***	−2.837*** (−4.227 to −1.446)	0.024$^{(0.13)}$ (−0.007 to 0.056)	**0.830***** (0.535 to 1.124)	0.024 (−0.014 to 0.062)	−0.001 (−0.005 to 0.003)	0.009 (−0.039 to 0.056)
	_0.577***_	_−1.993*** (−3.036 to −0.951)_	_0.007 (−0.028 to 0.041)_	_**tb$_{FFM}$ = 0.329***** (0.218 to 0.440)_	_0.012 (−0.027 to 0.051)_	_−0.002 (−0.006 to 0.003)_	_−0.006 (−0.051 to 0.039)_
NN$_{width}$	0.321***	−3.397*** (−5.112 to −1.682)	−0.010 (−0.051 to 0.031)	**0.851***** (0.487 to 1.215)	0.010 (−0.039 to 0.058)	—	—
	0.356***	−3.331*** (−5.003 to −1.658)	−0.004 (−0.044 to 0.037)	**0.836***** (0.481 to 1.191)	0.020 (−0.029 to 0.069)	**−0.004*** (−0.008 to 0.000)	—
	0.351***	−3.553*** (−5.339 to −1.767)	−0.004 (−0.045 to 0.036)	**0.882** *** (0.504 to 1.260)	0.018 (−0.031 to 0.067)	**−0.006*** (−0.011 to 0.000)	0.022 (−0.039 to 0.083)
	_0.414***_	_−3.008*** (−4.301 to −1.716)_	_−0.030 (−0.073 to 0.012)_	_**tb$_{FFM}$ = 0.387***** (0.250 to 0.525)_	_0.000 (−0.049 to 0.048)_	_**−0.007*** (−0.012 to −0.001)_	_0.010 (−0.046 to 0.066)_
NN endosteal diameter	0.204***	−3.840*** (−6.003 to −1.676)	−0.029 (−0.081 to 0.022)	**0.918***** (0.459 to 1.378)	0.003 (−0.059 to 0.064)	—	—
	0.291***	−3.725*** (−5.769 to −1.680)	−0.019 (−0.068 to 0.031)	**0.893***** (0.459 to 1.327)	0.021 (−0.038 to 0.080)	**−0.008**** (−0.012 to −0.003)	—
	0.281***	−3.820*** (−6.010 to −1.630)	−0.019 (−0.069 to 0.031)	**0.912***** (0.449 to 1.376)	0.020 (−0.040 to 0.080)	**−0.008*** (−0.015 to −0.001)	0.010 (−0.065 to 0.084)
	_0.328***_	_−3.234*** (−4.845 to −1.622)_	_−0.046$^{(0.09)}$ (−0.099 to 0.007)_	_**tb$_{FFM}$ = 0.398***** (0.226 to 0.570)_	_0.001 (−0.059 to 0.062)_	_**−0.009**** (−0.016 to −0.003)_	_−0.004 (−0.073 to 0.066)_
NN$_{CSMI}$	0.525***	−15.917*** (−21.213 to −10.622)	0.060 (−0.067 to 0.187)	**3.061***** (1.938 to 4.185)	0.124$^{(0.11)}$ (−0.027 to 0.275)	—	—
	0.521***	−15.982*** (−21.302 to −10.661)	0.054 (−0.075 to 0.182)	**3.076***** (1.946 to 4.205)	0.114$^{(0.15)}$ (−0.041 to 0.268)	0.004 (−0.008 to 0.017)	—
	0.542***	−17.929*** (−23.467 to −12.390)	0.050 (−0.076 to 0.176)	**3.478***** (2.306 to 4.650)	0.098 (−0.054 to 0.250)	−0.008 (−0.025 to 0.009)	**0.194*** (0.005 to 0.383)
	_0.591***_	_−15.240*** (−19.225 to −11.255)_	_−0.042 (−0.173 to 0.089)_	_**tb$_{FFM}$ = 1.469***** (1.044 to 1.895)_	_0.034 (−0.115 to 0.183)_	_−0.011 (−0.027 to 0.005)_	_0.140$^{(0.11)}$ (−0.033 to 0.312)_
NN$_{Z}$	0.532***	−11.646*** (−15.826 to −7.466)	0.077 $^{(0.13)}$(−0.023 to 0.178)	**2.155***** (1.268 to 3.042)	**0.125*** (0.006 to 0.245)	—	—
	0.557***	−11.810*** (−15.883 to −7.738)	0.062 (−0.036 to 0.161)	**2.192***** (1.327 to 3.056)	0.100$^{(0.10)}$ (−0.019 to 0.218)	**0.011*** (0.001 to 0.020)	—
	0.592***	−13.704*** (−17.864 to −9.543)	0.059 (−0.036 to 0.153)	**2.582***** (1.702 to 3.463)	0.084$^{(0.14)}$ (−0.030 to 0.198)	−0.001 (−0.014 to 0.012)	**0.189**** (0.047 to 0.330)
	_0.637***_	_−11.764*** (−14.750 to −8.778)_	_−0.011 (−0.109 to 0.087)_	_**tb$_{FFM}$ = 1.097***** (0.779 to 1.416)_	_0.036 (−0.076 to 0.147)_	_−0.004 (−0.016 to 0.009)_	_**0.149*** (0.020 to 0.278)_

All variables except PAL were analyzed in ln-transformed form. Lean mass–based models are presented in italics. Data for significant predictors appear in bold font.

[a] For buckling ratio, HFMTW was entered; for all other variables, HFPT was entered.

*$P < 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$ for t significance of β. For nonsignificant predictors, P values are shown in superscript parentheses.

95% CI, 95% confidence interval for beta; FN, femoral neck; tb$_{FFM}$, total body lean mass; NN, femoral narrow neck; BMC, bone mineral content; aBMD, areal bone mineral density; bCSA, bone tissue cross-sectional area; CT, cortical thickness; BR, buckling ratio; ED, endosteal diameter; CSMI, cross-sectional moment of inertia; Z, section modulus.

outcomes except FN_{Area} and NN_{CSMI}. Greater mean PAL was associated with greater FN_{BMC}, FN_{aBMD}, NN_{bCSA}, NN_{CT}, and NN_{Z}, but narrower bone width (NN_{width}), smaller endosteal diameter (NN_{ED}), and lower buckling risk (NN_{BR}), $P < 0.05$. For FN_{aBMD}, NN_{CT}, and NN_{BR}, both PAL and Tanner breast stage were stronger independent predictors than height.

When entered into models after Tanner breast stage, height, hip flexion index, and PAL, gymnast status exhibited significant associations with all bone outcomes except FN_{Area}, NN_{width}, and NN endosteal diameter, with a strong trend for lower NN buckling ratio in GYM ($P = 0.07$). After the entry of GYM status, Tanner breast stage remained a significant predictor of FN_{BMC}, FN_{aBMD}, NN_{bCSA}, NN_{CT}, and NN_{BR}. The addition of GYM status to the models further reduced associations between hip flexion indices and all bone outcomes ($P > 0.10$). In these models, height explained the greatest proportion of variance for all bone outcomes except NN cortical thickness and buckling ratio. For NN_{CT}, Tanner breast stage was the dominant predictor. For NN_{BR}, PAL was the dominant predictor, with significant associations also observed for Tanner breast stage and GYM status.

Finally, models based on total body non–bone lean mass were built, entering Tanner breast stage, tb_{FFM}, hip flexion index, PAL, and GYM status; height was purposefully excluded because of collinearity with tb_{FFM}. Lean mass exhibited significant positive associations with all bone outcomes except NN_{BR}. After the entry of tb_{FFM}, Tanner breast stage was no longer associated with any variables ($P > 0.08$) other than NN_{CT} and NN_{BR}. Again, after the entry of Tanner breast stage, tb_{FFM}, PAL, and GYM, no significant associations were observed between hip flexion indices and bone outcomes. Interestingly, physical activity exposure associations remained significant for NN_{width}, NN_{ED}, and NN_{BR} (greater activity: narrower bone geometry, lower buckling risk, $P < 0.05$), although the positive relationship between PAL and NN_{CT} was reduced to a strong trend ($P = 0.06$). GYM status remained a significant predictor of FN_{BMC}, FN_{aBMD}, NN_{bCSA}, NN_{CT}, NN_{Z}, and NN_{BR}, whereas the previously significant association between GYM status and NN_{CSMI} was weakened ($P = 0.11$). Lean mass explained the greatest proportion of variance for all bone outcomes, except NN_{BR}, for which PAL was the strongest predictor, followed by Tanner breast stage and GYM status (tb_{FFM}, $P > 0.70$).

To evaluate local versus distant muscle functional indices as predictors of FN skeletal properties, we applied the same model structures, simultaneously entering grip strength and hip flexion index, for head to head comparisons. In these analyses, HFPT was not a significant predictor of FN_{Area} in any of the model forms, whereas grip strength retained predictive value for FN_{Area} in all models ($P \leq 0.05$). For FN_{BMC}, both grip strength and HFPT were significant predictors before the entry of PAL, but with entry of PAL, both variables lost explanatory value ($P = 0.14, 0.10$); GYM entry restored some explanatory value to grip strength ($P = 0.10$). Of all the other variables and models, only NN_{Z} (section modulus) was predicted by HFPT ($P < 0.05$), but subsequent model building eroded its significance ($P \geq 0.10$); grip strength was not a significant predictor of NN_{Z} in any of the regression models.

DISCUSSION

As hypothesized, in this cohort of premenarcheal girls, dose of prior year, weight-bearing physical activity (PAL), and exposure to extreme dynamic loading (GYM status) were robust predictors of indices of FN structure. For many bone outcomes, the significant statistical effect of gymnast status persisted even after accounting for the effects of physical maturity, body size/lean mass, and activity. For all skeletal indices, except FN area, NN_{width}, NN endosteal diameter, and NN buckling ratio, GYM status was more strongly associated with dependent variables than PAL. These findings suggest that extreme dynamic loading may be more osteogenic than other weight-bearing activities, consistent with our previous reports of significant associations between gymnastic loading and FN skeletal indices (8). Nonetheless, PAL was a significant predictor of many FN skeletal indices, providing evidence of the osteogenic nature of a variety of nonaquatic loading modalities, many of which included a lower extremity dynamic loading component, including both high and odd impacts (e.g., soccer, lacrosse, and basketball). Our subjects' varied activity profiles did not allow for activity-specific analysis, other than for gymnastics.

For variables that represent periosteal and endosteal dimensions (FN_{Area}, NN_{width}, and NN_{ED}), associations between PAL and bone geometry were negative. Although GYM status was not a significant predictor for these variables, these PAL associations likely represent an inverse association between periosteal/endosteal dimensions and mechanical loading dose (PAL includes training hours for gymnastics and other activities). These findings corroborate our results from a more diverse cohort (Tanner breast stages I–V, pre- and postmenarche), in which dynamic loading dose (gymnastics) was inversely associated with both periosteal and endosteal dimensions, reflecting compact structure with a thicker, stronger cortical ring (8).

Contradicting our initial hypotheses, local indices of muscular strength and power were not robust, significant predictors of FN structure. Even before accounting for the effects of total body lean mass, for all bone variables, associations with local muscle force were weaker than those for prior year weight-bearing activity dose and exposure to extreme dynamic loading (as represented by HFPT or maximum total work, PAL, and GYM status, respectively). Furthermore, for all bone outcomes, ipsilateral leg (local) lean mass was not a stronger predictor than total body lean mass. Overall, these observations suggest an osteogenic role for mechanical loading via total body weight-bearing activity and via impact exercise, separate from and in addition to the action of local muscular forces and tissue factors. In these premenarcheal girls, local muscle forces do not appear to be tightly coupled with FN bone mass or geometry, at least not as indicated by Biodex hip flexion/extension indices. In fact, with the possible exception of NN section modulus, remote muscle strength (nondominant grip) was, if anything, a stronger predictor of FN outcomes than local muscle strength/power. It is possible that assessments of other hip muscular function, including hip abduction/adduction torques, may have yielded stronger or additional independent statistical effects to explain FN structure; future research should investigate these possibilities.

We were surprised by the superiority of grip strength over local muscle functional indices as a correlate/predictor of most FN bone outcomes. We had expected regional bone parameters to reflect regional loading and therefore regional muscle strength. It is possible that our ability to accurately measure grip strength was superior to our ability to measure hip strength (handheld dynamometer vs Biodex), particularly in these young girls of small body size. However, other investigators have noted the potency of grip strength as an indicator of muscle strength at other sites (38), as well as the superiority of grip strength versus local muscle strength assessments for predicting skeletal variability in both athletes and nonathletes (19,30,31). Thus, it seems unlikely that our findings should be attributed solely to methodological challenges. It is more likely that grip strength reflects overall maturity and body size to a greater extent than hip muscle functional indices, an assertion supported by a strong positive correlation between grip strength and tb_{FFM} in this cohort (r = 0.82, P < 0.001) and other reports of strong correlations between grip strength and indices of body size (38). Alternatively, it is possible that this finding is attributable to other unknown confounding factors.

As an indicator of physical maturity and estrogen exposure, self-assessed Tanner breast stage was a significant predictor of many FN bone outcomes. Even after accounting for the effects of height, local muscular function, physical activity dose, and exposure to extreme dynamic loading, Tanner breast stage explained additional variance for several outcomes, including bone mass, density, and cortical thickness (FN_{BMC}, FN_{aBMD}, bCSA, NN_{CT}, and NN_{BR}). In contrast, Tanner breast stage did not exhibit significant associations with indices of bone size and bone size–related strength (area, width, NN_{ED}, CSMI, and Z). As would be expected based on the relationship between physical maturity and lean mass, Tanner breast stage statistical effects were weaker in the lean mass–based model. Nonetheless, overall, our results support the concept of a strong positive relationship between estrogen exposure and dense, cortically robust bone structure (8,18,21,34).

Wetzsteon et al. (37) evaluated ankle dorsiflexion peak torque as a predictor of 38% tibia pQCT indices. Main models for subjects <21 yr old included age, tibia length, Tanner stage, race, sex, muscle CSA (pQCT, 66% site), peak torque, and body weight. In main models, peak torque demonstrated independent associations with polar section modulus (Zp), periosteal circumference, and cortical area. The addition of PAL and moderate/high activity to the main models did not eclipse peak torque predictive value. In these compound models, PAL and moderate/high activity demonstrated independent predictive value for periosteal circumference (P < 0.05), and PAL was an independent predictor of Zp (P < 0.05). The persistence of peak torque predictive value, despite the entry of activity variables into the model, differs from our results. This difference may be because our cohort included gymnasts whose exposure to dynamic loading activity is likely very different than that of Wetzsteon's subjects; thus, our subjects' more varied activity profiles may have yielded stronger associations between activity and bone outcomes. Alternatively, our contrasting results may reflect disparities in muscle forces at the hip versus the tibia. Notably, in both studies, total physical activity (or PAL) was an independent predictor of bone section modulus in models that include local muscle peak torque.

Daly et al. (5) evaluated maximum vertical jump height (VJH) and right knee extension and flexion peak torques as predictors of FN_{BMC}, FN_{width}, FN_{CSA}, and FN_Z in 103 prepubertal girls. PAL was low and uniform; 33% of subjects reported no organized activity (mean = 1.0 $h \cdot wk^{-1}$, SD = 1.4). Accordingly, correlations between local muscle peak torques and FN outcomes were most similar to those of our NON subgroup (Daly et al. r = +0.28 to +0.65; our NON r = +0.37 to +0.66, mean PAL = 3.8 $h \cdot wk^{-1}$). Similar to our results using total body lean mass, bone outcomes correlated more strongly with leg_{FFM} than with peak torques; leg_{FFM} was significantly, positively correlated with both peak torques. Despite limited activity variation, PAL was positively correlated with FN CSA and Z (P < 0.05). In contrast, VJH was not correlated with leg_{FFM}, peak torques, or any bone outcomes. In separate regression models entering femur/leg length, leg_{FFM}, VJH, and PAL: leg_{FFM} predicted FN_{BMC}, width, CSA, and Z; VJH was not predictive; and PAL predicted FN CSA and Z. In models entering femur/leg length, knee extension peak torque and PAL: knee extension and peak torque predicted FN_{BMC}, width, CSA, and Z, and PAL predicted Z. After adjusting for both femur/leg length AND leg_{FFM}, knee extension peak torque predicted FN_{BMC}, CSA, and Z; PAL predicted CSA and Z. Daly et al. concluded that leg_{FFM} may be used as a surrogate of local muscular peak force, despite the persistent statistical effect of local muscle peak torque. In our cohort, total lean mass, PAL, and GYM status encapsulated and eclipsed the statistical effect of local muscle function. This distinction may be attributed to greater overall variation in our cohort, with greater resultant explanatory value for maturity, PAL, and exposure to extreme dynamic loading, contrasting with the homogeneous Daly cohort.

Anliker et al. (1) evaluated gains in muscular force and pQCT-assessed bone mass after a 9-month, randomized controlled jumping intervention in 8- to 12-yr-old children (n = 22 intervention, n = 23 control). The investigators hypothesized

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that muscle force improvement would be strongly positively correlated with skeletal improvement. Pre- and postintervention, they identified a strong positive correlation between maximum voluntary ground reaction force (multiple one-legged hop, F_{m1LH}) and 14% tibia volumetric BMC ($r^2 = 0.51$–0.88). However, they detected no intervention-related differences for change in F_{m1LH} or BMC. Critically, absolute changes in F_{m1LH} were not related to absolute changes in BMC, implying the lack of tight coupling and/or different time courses for adaptation. Similar to our results, body size was a stronger correlate with bone indices than muscle function, whether evaluated in terms of raw values or changes. In our study, the assessment of GYM and PAL provided specific indices of extreme dynamic loading background exposure and nonaquatic weight-bearing activity, adding to model predictive power. Although Anliker et al. (1) did not quantify PAL, subjects were separated into intervention (jumpers) and control groups; the observed lack of group differences suggests that the intervention was insufficient to yield an effect, or that background (nonintervention) loading confounded the study.

Weeks et al. (36) performed an 8-month randomized controlled jumping intervention in 53 pubertal girls (age: mean = 13.7, SD = 0.5 yr, 74% postmenarche). Restricting the discussion to females and FN outcomes, significant $\mathrm{FN_{BMC}}$ improvements were reported in jumpers (14%) versus controls (5%), although significant differences were not detected for rate of change in $\mathrm{FN_{Area}}$, bone mineral apparent density, or CSMI. Interestingly, VJH improvements were not significant. The fact that jumpers improved $\mathrm{FN_{BMC}}$, but not VJH, suggests that bone gains were a function of growth and exposure to dynamic loading via impact exercise, not a result of increased muscle forces. Regression results supported this idea, attributing significant $\mathrm{FN_{BMC}}$ gains in the intervention group to total body lean mass gains, whereas background PAL and VJH were not significant predictors. On the whole, the results of the study by Weeks et al. (36) support the view that dynamic loading via impact exercise stimulates $\mathrm{FN_{BMC}}$ accrual, independent of muscular function.

Limitations

Hip structural analysis variables can exhibit greater CV than most other DXA outcomes, as they are particularly influenced by positional variation (16). In our laboratory, the CV for $\mathrm{NN_{CSMI}}$ and $\mathrm{NN_Z}$ were particularly high (assessed in middle-age women); for these variables, underlying positional variation may have hampered detection of muscle function associations.

Similarly, isokinetic strength testing can exhibit high CV in pediatric subjects, especially if pediatric modifications, warm-up, familiarization, rest periods, and verbal feedback are not included (6). Thus, we specifically designed our Biodex protocols to optimize testing conditions, incorporating these key elements to maximize reliability and validity of results (minimize CV and maximize accuracy). In the current analysis, CV were 12.6% and 10.0%, within the acceptable range for large muscle groups (≤15%) per manufacturer recommendations (3). Nonetheless, this variability may have affected our capacity to detect significant associations between hip muscle function indices and bone outcomes.

For practical reasons, we limited our analyses of local muscular function to HFPT or maximum total work. It is possible that an index of hip abduction/adduction or a more complex measure of hip function would have been a stronger predictor of local bone mass, structure, and strength indices. On this basis, our conclusions regarding the osteogenic role of capacity for force generation are limited to isometric hip flexion at the recommended pediatric angular velocity of $60°\cdot\mathrm{s}^{-1}$.

Finally, HSA variables were developed and validated for the estimation of skeletal parameters in adults. Accordingly, it may be problematic that HSA estimates $\mathrm{NN_{bCSA}}$ based on a uniform, adult tissue vBMD standard because tissue mineralization varies by age and loading status. These issues should be less problematic when comparing subjects of similar age and maturity and accounting for differences statistically. Nonetheless, it is possible that HSA underestimates loading-related bCSA advantages, with concomitant underestimation of loading-related advantages in bone geometry and strength (including endosteal diameter decrements) (8). Although HSA bone strength indices are of limited clinical relevance for healthy pediatric subjects, HSA provides safe, inexpensive assessments of FN structure for pediatric longitudinal studies. Importantly, HSA allows evaluation of pediatric skeletal structure as the foundation for the adult skeleton.

CONCLUSIONS

At the FN of premenarcheal girls, skeletal indices are a function of physical maturity and body size (total body lean mass) and/or reported physical activity (PAL). Body size ($\mathrm{tb_{FFM}}$) and grip strength, an index of remote muscle function, are superior to indices of local muscle strength as predictors/correlates of FN skeletal parameters. The observed relationship between local muscle flexion strength/power and FN structure is encapsulated and/or eclipsed by physical maturity, body size, and physical activity exposure. The observed associations with activity dose (PAL) provide evidence that nonaquatic exercise is osteogenic during growth. In addition, GYM status statistical effects suggest the independent benefit of greater activity doses and extreme dynamic loading modalities.

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