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Skeletal loading: Lean and bone mass development in young elite male gymnasts, swimmers and non-athletes aged 6 to 24 years.

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Abstract

Background: Exercise optimises peak bone mass accrual, particularly if the loading is high magnitude and distributed in abnormal directions. Little is known about the influence of early intense training in sport during peak bone mass (PBM) accrual, especially in boys.

Methods: Ninety-eight males aged 6 - 24y: (gymnasts, swimmers, controls) completed the bone-specific physical activity questionnaire (BPAQ) and a 7 day exercise diary. Dual energy X-ray absorptiometry determined bone mineral properties of the total body (less head, TBLH) and lumbar spine (LS, L1-L4), and total lean mass. Sub-group analyses were conducted for juniors (pre-pubescent), adolescents (11- 16 y) and seniors (17-24 y).

Results: Lean mass was positively associated with TBLH and LS bone outcomes in all three age groups (R^2= 0.632 - 0.770, $p < 0.05$) and BPAQ scores were associated with LS BMD in adolescents and seniors (R^2 = 0.440 and 0.591, $p < 0.05$). Senior gymnasts had significantly higher LS BMD (g.cm2) and Z-scores than swimmers ($p = 0.004$) and controls ($p = 0.012$).

Conclusions: Elite gymnastics is associated with superior peak bone mass accrual in young males. The benefits appear more pronounced during young adulthood compared to pre-puberty, potentially reflecting an extended time course for bone adaptation.

Key words: Exercise, bone, growth, peak bone mass.

Introduction

The incidence of osteoporosis is increasing due to the ageing population and unfavourable lifestyle factors such as insufficient physical activity (12, 69). One major preventative measure against the development of osteoporosis is the optimisation of peak bone mass (PBM) throughout the early years (1, 60). Bone mass increases substantially during the first two decades, which has been found to reach a plateau approx. 7 years after Peak Height Velocity (PHV) in both males and females, equating to 20.5 years and 18.8 years, respectively (5).

However, the accrual of bone is not a uniform process, with bone developing most rapidly in adolescent years, where approximately 50 to 60% of total adult bone mass is acquired within this time period (29). One key and modifiable strategy for enhancing PMB accrual is regular weight bearing exercise (3, 6, 31, 47, 54, 72), with bone mechanoadaptation enabled through both gravitational loading and muscular eccentric and torsional contractions (21, 56). The osteogenic efficacy of exercise appears to be especially prominent prior to closure of the epiphyseal plates, and numerous studies have reported the existence of a 'window of opportunity' during early puberty and adolescence (31, 37, 42, 48, 60).

Weight-bearing exercise prior to the pubertal growth spurt stimulates an increase in both bone and skeletal muscle size to a greater degree than is observed with normal growth in children who are not physically active (24, 35, 63), but more research is required to fully understand the extent or timing of this bone mechanoadaptation via different exercise modes in young males.

Gymnastics and swimming are considered ‘early specialisation’ sports and involve long hours of training, superior muscular development and contrasting magnitudes of forces on the skeleton prior to maturation.

A body of work, mainly in females, indicates superior bone strength in gymnasts compared to their peers and athletes from other sports (7, 8, 14, 16, 34, 39, 52, 56). Gymnastics generates forces of up to ten times body weight (47), and in abnormal directions, providing a prime model of mechanical loading. This is supported by studies demonstrating GRFs in gymnastics of between 5 - 13 times body weight (28, 66). Indeed, superior spine and femoral neck bone strength has been reported in female gymnasts compared to runners and non-athletic women, over a period of 7 years (56). However, young males have not been considered in such detail.

Research concerning the effects of swimming on PBM accrual in swimmers has produced mixed results (13, 15, 19, 32, 64). A meta-analysis encompassing 14 studies concluded that, during childhood and adolescence, swimmers possess bone strength comparable to their non-active peers (23). However, they exhibit lower bone strength compared to athletes participating in other sports. Furthermore, this disparity in bone strength between swimmers and their counterparts in other sports becomes more pronounced with age. Given swimmers train in an environment where the skeleton does not experience the loading or impact associated with other sports, these findings would concur with the theory related to mechanoadaptation.

However, lean mass has also been positively associated with bone properties (33, 57) and in a longitudinal study, it was found that physical activity had a significant time dependent effect on lean mass accrual in boys during adolescence (4).

As performance swimmers are likely to have a greater lean mass via their involvement in sport, but are not exposed the extent of gravitational loading as other athletes during growth, this warrants further exploration.

Understanding how specialization in sports such as gymnastics or swimming impacts bone mass during the PBM period is crucial for creating effective exercise training programs and interventions. There is also limited research available concerning young male gymnasts throughout the various stages of PBM development and in terms of total body and lumbar spine bone status.

Therefore, the focus of this study was to assess skeletal loading and bone mass in the total body and spine of young elite male gymnasts, swimmers, and non-athletic controls due to the variation in mechanical loading. By exploring outcomes in a broad age range (6-25 years) considering maturational stages: junior, adolescent, and senior sub-groups.

Hypothesis

1. Young male gymnasts will present with superior bone mass accrual when compared with age matched swimmers and controls.
2. Lean mass will be positively associated with bone mass variables.

By adding to the literature, this study also sought to find out when, during growth, the benefits of skeletal loading appear to be more pronounced, whilst exploring the relationship between lean mass and loading of the whole body and lumbar spine in these specific populations, linked to loading modality.

Materials and methods

Athletes were recruited from gymnastics and swimming clubs offering intense systematic performance training, and non-athlete controls were recruited from a local school and the local community. These participants were not involved in any competitive sport or be involved in any single activity for more than an hour a week. The sports were chosen due to the variation in mechanical loading (high *versus* low impact). The definition of a gymnast or swimmer was a participant currently involved on a sports performance pathway or engaged in regular performance-based sport-specific exercise training which varied from 2 to 8 sessions a week, dependent on age and stage. The minimum age for inclusion in the study was 6 years, because this is the entry age for early specialisation in sport including gymnastics and swimming (16, 45). Twenty-five years because the majority of PBM has been accrued by the end of the second decade (5, 30). Maturational stage and subsequent grouping (junior, adolescent or senior) was determined by self-assessed Tanner staging (41, 61, 64). This allowed children to self-assess and identify their maturity status based on developmental diagrams of genitalia and pubic hair (61). Previous research indicated that age ten and under would be at Tanner stage 1 (43). All participants gave their informed assent (and / or consent) before completing a questionnaire which provided details of their current and previous sports participation and medical history. Full ethical approval for the junior and adolescent study was granted by [redacted]

Assessment of skeletal loading

All participants, (with parent or guardian help where appropriate), completed a screening questionnaire on medical history, previous and current sports training and competition standards. and previous and current injuries. Injuries were noted for background information, in case of any link to absences in training times. The Bone Specific Physical Activity Questionnaire (BPAQ) (68), was used to obtain data on lifetime bone-specific physical activity. The type, frequency and years of physical activity participation were recorded for each year since age 1, and for current physical activity levels defined as exercise within the last 12 months. All hours of physical activity were considered in addition to school physical education / sports lessons. From this data, total cumulative scores for bone specific loading were derived.

Anthropometry

All measurements were taken with shoes and jewellery removed and participants wore lightweight clothing. Standing and sitting height were recorded to the nearest 0.1cm using a stadiometer (SECA, Birmingham, UK). Body mass was measured using calibrated electronic scales (SECA, Birmingham, UK) and recorded to the nearest 0.1 kg.

Assessment of bone and body composition

Participants received one total-body and one lumbar spine dual energy X-ray absorptiometry (DXA) scan (GE Lunar iDXA, GE Healthcare, UK) in a euhydrated state in accordance with recommendations (Nana *et al*., 2015). This scan provided the Body Mass Index (BMI) and lean mass results. The total body and lumbar spine were chosen as sites of interest, as recommended by the ISCD Official Position on the most appropriate and reproducible sites for paediatrics (2, 73). For the total-body scan, participants were scanned supine with ankles supported using the Lunar positioning strap (0.5 cm space between the ankles). Total-body BMD, bone mineral content (BMC), lean tissue mass and fat mass were derived. For participants under the age of 20 years, outputs were analysed as total body less head (TBLH) which is recommended for improving the accuracy of BMC and BMD measurements in young people (2). At the time of the study, TBLH was not available for adults. Lumbar spine BMD (L1 to L4) was evaluated and age and sex-specific UK reference data were used to calculate BMD Z-scores. For all lumbar spine scans, positioning was assisted with the GE-Lunar spine positioner which elevates the legs and opens the inter-vertebral spaces to allow clear visualisation of the vertebra. The analysis of all scans were performed by the same experienced densitometrist, who ensured appropriate lumbar vertebrae segmentation. Quality assurance and quality control observations were recorded according to manufacturer's guidelines throughout the duration of the study; no calibration drifts were reported during the period of study.

Statistical analysis

IBM SPSS Statistics Version 20.0 (IBM, Armonk, NY, USA) was used for all data analysis. Descriptive statistics were calculated for all variables and presented as means and their standard deviations (±). A Shapiro-Wilks normality test was used for testing normality and equality of variance. Differences between groups non-athletes were tested using analysis of variance with the Bonferronni post-hoc test for normally distributed data. When data were not normally distributed (BPAQ scores), the Mann Whitney U test was used. Effect sizes using partial eta squared (η^2) were calculated and interpreted as follows: 0 to 0.1 = small, 0.1 – 0.3 = modest and 0.3 – 0.5 = moderate and > 0.5 = large (Cohen et al., 2013).

Findings / Results

Demographics and body composition data

Ninety-eight males (aged 6 to 24 years) were recruited from the local elite gymnastics and swimming clubs, and from a local school. (The breakdown of each sub-group is illustrated in Table 1). There were no differences in age between junior gymnasts, swimmers and controls (8.5 ± 1.2 y), and no differences in weight, BMI, lean body mass and percentage body fat (Table 1). Mean percentile standing height for age, was lower in gymnasts (38.5 ± 29.2%)

than swimmers (75.8 ± 28.2%) and controls (70.7 ± 19.6%) (p = 0.039, p = 0.026, respectively; η_p^2 = 0.328).

In the adolescent group, there were no differences in age or Tanner stage between gymnasts, swimmers and controls. Percentile standing height for age was lower in adolescent gymnasts compared to swimmers (30.7 ± 23.5% v 55.9 ± 26.6%; p = 0.038, η_p^2 = 0.118). There were no differences in BMI or absolute lean body mass. However, the percentile of lean body mass for height was greater in adolescent gymnasts compared to controls (81.6% v 57.8%, p = 0.05, η_p^2 = 0.168). There were no differences in age between senior, gymnasts, swimmers and controls (Table 1). Senior gymnasts were shorter than swimmers (169.9 v 180.5cm; p = 0.021, η_p^2 = 0.256) and had lower percentage body fat than controls (13.9 v 20.2%; p = 0.003, η_p^2 = 0.322).

Table 1. Demographic and body composition outcomes

	Juniors (n=27)			*Adolescents (n= 39)*			*Seniors (n=32)*		
	Gym (n=11)	Swim (n= 5)	Controls (n=11)	Gym (n=13)	Swim (n=12)	Controls (n=14)	Gym (n = 14)	Swim (n=6)	Controls (n=12)
Age (yrs)	8.4 ±1.0	8.9 ±1.4	8.3 ±1.3	13.2 ±1.9	13.5 ±1.6	13.3 ±1.1	21.2 ±2.1	20.4 ±1.9	21.8 ±1.9
Weight (kg)	24.9 ±2.7	30.4 ±7.4	28.8 ±8.0	43.9 ±8.6	50.6 ±13.9	49.7 ±10.8	69.1 ±7.4	76.3 ±10.6	73.9 ±6.6
Height (cm)	128.0 ±4.5	138.4 ±9.4	133.4 ±9.5	151.8 ±11.0	160.8 ±14.6	159.4 ±12.4	**169.9 ±8.2**[a]	**180.5 ±5.0**	176.4 ±7.6
Height for age (%)	**38.5 ±29.2**[ab]	**75.8 ±28.2**	**70.7 ±19.7**	**30.7 ±24.0**[a]	**55.9 ±26.0**	49.9 ±34.0			
Body mass index (kg.m^{-2})	15.2 ±0.9	15.6 ±1.8	15.9 ±2.0	18.9 ±1.7	19.1 ±2.0	19.2 ±2.4	23.9 ±1.7	23.3 ±2.0	23.8 ±2.3
Percentage body fat	19.8 ±5.4	21.1 ±3.2	23.2 ±5.2	**15.9 ±4.6**[b]	18.7 ±4.2	**21.4 ±6.3**	**13.9 ±4.4**[b]	15.6 ±3.5	**20.2 ±4.7**
Lean body mass (kg)	19.3 ±2.3	22.7 ±5.2	20.8 ±4.7	35.5 ±7.9	39.7 ±12.3	37.3 ±9.0	56.9 ±7.0	61.3 ±6.4	57.0 ±4.4
Lean body mass for height (%)	48.8 ±23.2	31.4 ±18.0	40.8 ±18.9	**81.6 ±19.0**[c]	61.3 ±14.4	**57.8 ±30.1**	60.1kg	50.8kg	56.7kg
	[a]gymnasts < controls, *p = 0.026,* [b]gymnasts < swimmers, *p = 0.039;* η_p^2 = 0.328			**[a] gymnasts < swimmers (*p = 0.03;* η_p^2 = 0.118*)* , [b] gymnasts < controls, *p = 0.036;* η_p^2 = 0.168, [c] gymnasts > controls (*p = 0.05;* η_p^2 = 0.168**			**[a] gymnasts < swimmers, *p = 0.021;* η_p^2 = 0.256 [b] gymnasts < controls, *p = 0.003;* η_p^2 = *0.322***		

Bone specific physical activity

Junior: Junior gymnasts were participating in more hours of physical activity a week (7.6 ± 2.9 h/wk), than controls (4.7 ± 2.5 hrs/wk) ($p = 0.069$, $\eta_p^2 = 0.208$). There were no differences between gymnasts and swimmers in relation to the time spent involved in physical activity per week, and the majority of junior swimmers and gymnasts competed at a competitive club level. Two gymnasts and one swimmer were competing at regional level. The junior gymnasts' BPAQ scores were significantly higher than those of the swimmers and controls, representing a greater exposure to skeletal impact loading through sport. ($p < 0.001$, $\eta_p^2 = 0.932$).

Adolescents: Compared with controls and swimmers, adolescent gymnasts were involved in more hours of physical activity per week (17.3 ± 2.4 v6.2 ± 2.8 hrs/wk; $p < 0.001$) and (12.5 ± 4.6 hrs/wk; $p = 0.013$) respectively ($\eta_p^2 = 0.661$). All adolescent gymnasts and swimmers were competing at either regional or national level and had been involved in the sport for 7.25 ±1.8yrs (gymnasts) 4.92 ± 2.4yrs (swimmers). BPAQ scores were greater in gymnasts than both swimmers and controls ($p < 0.001$; $\eta_p^2 = 0.904$).

Senior Level: All senior sports performers were at competing at national level, with ten gymnasts competing at international and world championship level. One swimmer was competing at international level. Senior gymnasts were involved in significantly more hours of physical activity per week (26.3 ± 5.6 hrs/week) than controls (6.2 ± 4.2hrs/wk) and swimmers (16.4 ± 6.4 hrs/wk) ($p < 0.001$), and senior swimmers engaged in more physical activity than controls ($p = 0.002$, $\eta_p^2 = 0.782$). Senior gymnasts had been competing in the sport for 14.4 ±1.6 yrs and swimmers for 9.2 ± 2.6 yrs.

BPAQ scores were greater for gymnasts than swimmers and controls, indicating previous and current exposure to greater skeletal loading ($p < 0.001$; $\eta_p^2 = 0.854$)

Table 2. Bone specific physical activity scores for age and sports group

	Juniors (n=27)			*Adolescents (n= 39)*			*Seniors (n=32)*		
	Gym	Swim	Controls	Gym	Swim	Controls	Gym	Swim	Controls
Hours of physical activity per week	**7.6 ±2.9**^{a}	7.2 ±3.4	**4.7 ±2.5**	**17.3 ±2.4**^{ab}	12.5 ±4.6^{c}	6.2 ±2.8	**26.3 ±5.6**^{a,b}	**16.4 ±6.4**^{c}	6.2 ± 4.2
	a gymnasts >controls, p=0.049;			***^{a} gymnasts > controls, p < 0.001, ^{b} gymnasts > swimmers , p = 0.013***			***^{a} gymnasts > swimmers, p < 0.001, ^{b} gymnasts > controls, p < 0.001, ^{c} swimmers > controls, p = 0.002***		
BPAQ – total	**70.6 ±11.7**^{a,b}	**9.3 ±2.9**	**11.7 ±5.7**	**339.5 ±83.9**^{a,b}	**16.8 ±12.2**^{d}	**30.1 ±12.7**	**405.2 ±119.6**^{a,b}	10.4 ±10.1	25.0 ±16.0
	^{a} gymnasts > swimmers, *p* < 0.001,^{b} gymnasts > controls, (*p* < 0.001; η_p^2 = 0.932)			***^{a}gymnasts > swimmers, p < 0.001, ^{b} gymnasts > controls, p < 0.001; η_p^2*** **= 0.904** ***^{c} swimmers > controls, p < 0.003, ^{d} swimmers > controls, p < 0.013***			***^{a} gymnasts > swimmers, p < 0.001, ^{b} gymnasts > controls, p < 0.001; η_p^2 = 0.854***		

Bone Mass

Table 3. Bone status of male gymnasts, swimmers and age matched controls

	Juniors (n=27)			*Adolescents (n= 39)*			*Seniors (n=32)*		
	Gym	Swim	Controls	Gym	Swim	Controls	Gym	Swim	Controls
TBLH BA (cm)	1077.8 ±89.6	1251.0 ±241.9	1106.8 ±226.9	1656.7 ±270.1	1830.8 ±407.7	1783.6 ±297.3			
Total Body BA (cm)							2415.9 ±259.9	2435.8 ±178.9	2578.8 ±175.0
Total body BMC (g)	986.7 ±155.7	1225.1 ±354.2	1088.1 ±209.1	1869.1 ±424.3	2080.3 ±670.6	2057.2 ±495.0	3075.6 ±452.9	2961.3 ±193.4	3022.6 ±334.3
TBLH BMC(g)	663.8 ±137.9	863.1 ±305.6	744.5 ±181.3	1663.8 ±137.9	1662.0 ±604.2	1639.3 ±456.4			
Total BMD (g.cm^2)	0.753 ±0.047	0.815 ±0.099	0.783 ±0.056	0.955 ±0.095	0.983 ±0.136	1.00 ±0.096	1.292 ±0.082	1.259 ±0.089	1.239 ±0.082
TBLH BMD (g.cm^2)	0.637 ±0.076	0.674 ±0.112	0.638 ±0.065	0.856 ±0.103	0.879 ±0.143	0.905 ±0.105			
Total body BMD for age (%)	100.9 ±5.0	106.2 ±5.9	105.0 ±4.2	105.0 ±4.6	104.0 ±4.6	108.0 ±6.3			
Total body Z-score	0.4 ±0.7	0.9 ±0.8	0.8 ±0.7	0.7 ±0.6	0.6 ±0.6	0.9 ±0.8	**0.8** ±0.9	0.2 ±0.3	0.4 ±0.6
BA for height (%)	27.3 ±22.5	30.4 ±27.6	23.5 ±18.5	**81.3 ±21.4**	65.6 ±31.2	66.6 ±28.7			
BMC for bone area (%)	63.8 ±28.2	61.0 ±22.7	65.7 ±21.6	52.5 ±28.9	**38.5 ±26.5**	51.4 ±26.3			

BMC for lean body mass (%)	39.0 ±24.4	56.8 ±30.1	46.4 ±33.9	49.1 ±27.5	48.5 ±25.2	64.6 ±27.6			
Lumbar spine, L2-L4 BA (cm^2)	22.4 ±2.0	25.6 ±3.4	23.0 ±3.1	32.6 ±5.34	36.6 ±9.0	35.9 ±6.5	46.8 ±5.5	51.0 ±4.5	48.5 ±5.2
Lumbar spine, L2-L4 BMC (g)	16.3 ±2.3	19.6 ±5.9	16.0 ±2.1	32.2 ±11.1	36.5 ±15.8	34.4 ±10.1	66.6 ±9.3	61.2 ±9.8	62.0 ±10.7
Lumbar spine L1-L4 BMD (g.cm^{-2})	0.696 ±0.072	0.726 ±0.130	0.689 ±0.016	0.967 ±0.164	0.944 ±0.224	0.935 ±0.118	**1.391**[ab] **±0.119**	**1.174 ±0.138**	**1.237 ±0.123**
Lumbar spine L1-L4 Z-score	0.4 ±0.8	0.1 ±1.0	-0.2 ±0.7	**0.6** ±0.6	0.1 ±1.0	0.2 ±0.7	**1.3**[cd] **±0.9**	**-0.4 ±1.0**	**0.1 ±1.0**
	No significant differences between groups			No significant differences between groups			[a] ***swimmers < gymnasts, p = 0.004,*** [b]***controls < gymnasts, p = 0.013,*** η_p^2 **= 0.367** [c]***swimmers < gymnasts, p = 0.004,*** [d]***controls < gymnasts, p = 0.012;*** η_p^2 ***= 0.368***		
TBLH = total body less head, BA = bone area, BMC = bone mineral content, BMD = bone mineral density									

Senior gymnasts had significantly greater lumbar spine BMD and Z-scores than swimmers (p = 0.004; η_p^2 = 0.367) and controls (p = 0.012; η_p^2 = *0.368*) (Table 3). These results are also demonstrated on Figures 1 and 2 below.

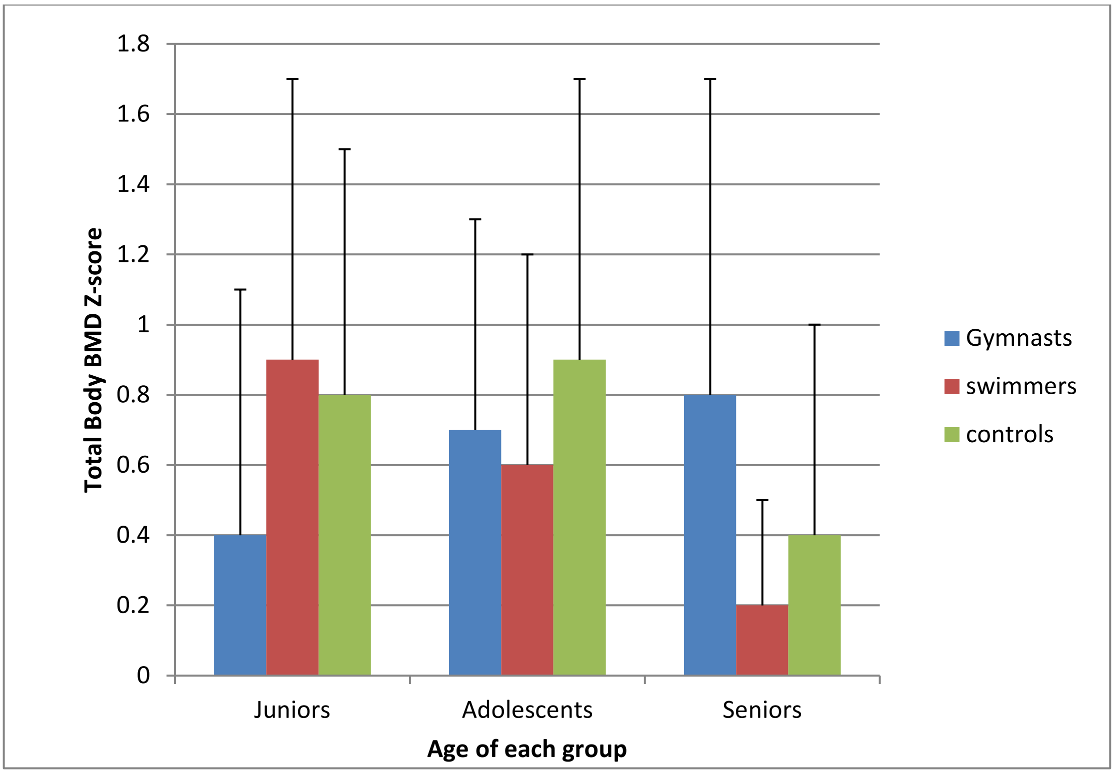

Figure 1. Total body BMD Z-scores in gymnasts, swimmers and controls

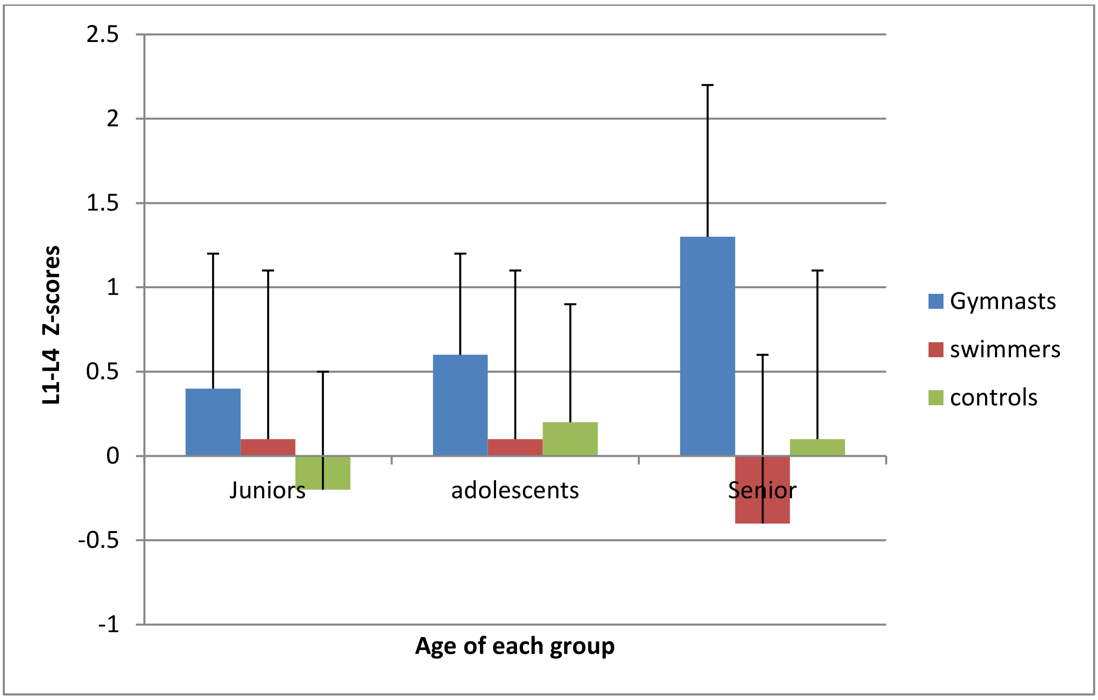

Figure 2. Lumbar spine (L1-L4) BMD Z-scores (+ SD) for each group by age

Variables associated with total body bone status

Correlation coefficients were adjusted for height, and in the case of the adolescents, Tanner stage.

Juniors: In the junior age groups, only two variable correlated. Lean mass correlated with both TBLH BMC ($R^2 = 0.604$; $p = 0.003$) and TBLH bone area ($R^2 = 0.478$, $p = 0.028$).

Adolescents: In this age group, there was a stronger correlation between lean mass and TBLH BMC ($R^2 = 0.967$, $p < 0.001$) and a positive association between lean mass and total body Z score ($R^2 = 0.349$, $p = 0.037$). Tanner stage was also correlated with TBLH BMC (g) ($R^2 = 0.785$, $p < 0.001$), TBLH BMD ($R^2 = 0.723$, $p < 0.001$) in the adolescent group. However, there were no associations between total body bone status and BPAQ scores in juniors or adolescents.

Seniors: In the senior participants, lean mass was associated with total body BMD ($R^2 = 0.632$, $p = 0.050$) whilst BMI was also associated with total body BMD ($R^2 = 0.801$, $p = 0.005$) respectively, regardless of sport participation. Interestingly, in this group, BPAQ score was associated with both total body BMD ($R^2 = 0.549$, $p = 0.003$) and total body Z-score ($R^2 = 0.510$, $p = 0.006$).

When all participants were combined into one group, lean body mass correlated positively with total body BMC ($R^2 = 0.401$, $p = 0.001$,) and total body BMD ($R^2 = 0.576$, $p < 0.001$), whilst the BPAQ score correlated with total body BMC.

Lumbar spine bone status

Juniors: There were no associations with lumbar spine BMC, BMD and Z-scores.

Adolescents: BPAQ score was found to be positively associated with the following lumbar spine properties in the adolescent group:

L2-L4 BMC ($R^2 = 0.472$, p = 0.007); L1–L4 Z-scores ($R^2 = 0.440$, p = 0.013) and L1–L4 BMD (g/cm2) ($R^2 = 0.481$, p = 0.006).

Lean body mass was found to strongly correlate with:

L2-L4 BMC ($R^2 = 0.831$, p < 0.001); L1 – L4 BMD (R2 = 0.645, p < 0.001) and L2-L4 BA (R2 = 0.725, p < 0.001)

BMI correlated with L2-L4 BMC ($R^2 = 0.608$, p < 0.001); L1 – L4 BMD ($R^2 = 0.537$, p = 0.005) and L2-L4 BA ($R^2 = 0.534$, p = 0.005).

Tanner stage was also found to associate with L2-L4 BA ($R^2 = 0.340$, p = 0.049).

Seniors: In senior participants, BPAQ score was associated with lumbar spine L1-L4 BMD ($R^2 = 0.591$, p = 0.001). BPAQ score also correlated with lumbar spine L1-L4 Z-score ($R^2 = 0.600$, p = 0.001).

In this age group, the number of years involved in competitive sport was also correlated with the lumbar spine BMD (R2 = 0.378, p = 0.043) and L1-L4 Z-score (R2 = 0.389, p = 0.037). Percentage body fat was negatively associated with lumbar spine L1-L4 BMD (R2 = -0.366, p = 0.043) and L1-L4 Z-score (R2 = -0.378, p = 0.036).

<u>All groups</u> - Finally, when all stages of participants were combined and considered, BPAQ was found to be associated with all of the following variables:

L2-L4 BMC ($R^2 = 0.370$, p = 0.034)

L1-L4 BMD ($R^2 = 0.491$, p < 0.001) and

L1-L4 Z-score ($R^2 = 0.296$, p = 0.011) showing a strong association between skeletal loading across the lifespan and lumbar spine bone status.

BMI was also found to be associated with lumbar spine BMD ($R^2 = 0.662$, p < 0.001) and lumbar spine Z-score ($R^2 = 0.294$, p = 0.045).

Discussion

Our study revealed a distinct differentiation in bone strength during the peak bone mass period based on sports specialization. Importantly, gymnasts consistently demonstrated higher lumbar spine BMD across all maturation groups, achieving statistical significance in the senior group. Furthermore, senior gymnasts also had greater total body BMD compared to their age-matched peers in swimming and in controls.

These findings underscore the potential osteogenic advantage of gymnastics for males. Ground reaction forces, or ‘loading in situ’ was not evaluated, but the BPAQ results across the lifespan would tend to support these conclusions. Engaging in gymnastics from a young age appears especially beneficial as the sport’s inherent combination of gravitational and torsional loading can effectively trigger bone mechano-adaptation (46). Our focus on artistic gymnasts, who undergo rigorous upper body training and repetitive ground forces, through significant strength and conditioning, further emphasized this observation. The multiple apparatus utilized by male gymnasts—such as the floor, pommel horse, rings, vault, parallel bars, and high bar—all necessitate force exertion, particularly during inverted body positions like handstands, leading to diverse spine loading (61). The notion of the muscle–bone mechanical link and the shift of focus from purely loading magnitude to loading regimes in bone mechanobiology, has also been suggested (71), and something that warrants scientific consideration. Research into quantification of loading ‘in situ’, within the training environment over time would be beneficial to help support performance discussions.

The osteogenic advantages of gymnastics were most evident among adolescents and seniors, contrasting with juniors. This observation aligns with the knowledge that bone accrual and bone elongation strengthen during Tanner stage 2, driven by sex steroids and growth hormone surges (40, 42). Coinciding with such physiological changes, mechanical loading may optimally stimulate bone response, especially since adolescence has been identified as a crucial window for bone accrual (36, 42, 44, 55).

For senior gymnasts, prolonged exposure to bone loading due to increased training volumes and competitive commitments correlated with superior total and lumbar spine BMD compared to swimmers and non-athletes. Conversely, swimming, a non-weight-bearing sport, offers limited gravitational skeletal loading. This supports previous work (26, 53) and was evident in swimmers' consistently lower BPAQ scores and inferior lumbar spine BMD relative to gymnasts, though the difference with controls was statistically insignificant.

Lean body mass was a primary determinant of bone properties, confirming previous findings (27, 65). Our data further illuminated the intricate relationship between lean mass and bone, particularly during pre-puberty and adolescence, suggesting its supremacy over loading modality during this period of maturation. However, an intriguing divergence was noticed in lumbar spine BMD correlations with lean body mass among the different age groups, pointing toward potential influential factors such as the emphasis on upper body strength and lean muscle mass during puberty in males, and the intensive training on gymnastic apparatus during this pivotal developmental phase.

There was no significant difference in the adolescent group in terms of Tanner staging, but, when looking at varying results across the sports for both total body Z-scores and lumbar spine Z-scores, the greatest difference lay between adolescent and senior gymnast, suggesting that the skeleton's gravitational loading might be most effective during the accelerated growth phase in late adolescence (11, 59). Conversely, swimmers displayed a declining trend in total body Z-scores, further accentuating the potential "window of opportunity” for optimizing lumbar spine bone status in exercising male athletes during late adolescence.

In controls, the scores remained more consistent across the subgroups. It is also worth noting that many of the ‘non-athletic controls’, who volunteered were still involved in some recreational levels of physical activity. The form of mechanical loading exerted on bones (weight bearing and directional forces via muscular contraction) during specific sports might need to be considered in addition to the duration of physical activity.

Our findings advocate the mid-twenties as a pivotal juncture for bone-enhancing interventions, resonating with the consensus that peak bone mass development extends till late twenties (5, 67).

Limitations

Although this study provides valuable insights, several considerations should be made. First, the study presented relatively small sample sizes, particularly when divided across the age groups and sports. The cross-sectional design also restricts the ability to establish causal relationships. This prevents us from assessing longitudinal changes in bone strength as a result of continued sports participation. We also do not have information in this cohort on bone microarchitecture, such as trabecular bone score, which would have improved understanding on this further important dimension of bone strength. Additionally, there are other factors such as nutritional intake, genetic predisposition, and other lifestyle variables, which have essential roles in peak bone mass accrual. However, in terms of exposure to exercise and sports specializations, the groups were well defined. Future, longitudinal research would be particularly beneficial to provide a clearer understanding of the sustained impacts of sports specialization on bone health over time and throughout the life-course.

Accelerometers have been used to estimate forces in running (70) and also employed to assess physical activity experienced during a typical day (10, 51). However, it is vital to recognise that this study design was not attempting to quantify isolated physical activity, but instead look at all the factors contributing to bone mineral accrual. The BPAQ questionnaire provided an opportunity to do this, although there is a recognition that the use of questionnaires to collect data can allow for a certain degree of error when reporting variables.

Conclusions

This study aimed to consider factors contributing to bone mineral accrual across the lifespan of young males involved in weight bearing and non-weight bearing sports.

Lean mass was found to be positively associated with total body bone status outcomes in all three age groups regardless of sporting background or BPAQ score. Lean mass also positively associated with lumbar spine bone variables in the adolescent and senior groups. However, despite there being no significant difference in lean mass between the three activity groups, regardless of age, senior swimmers and controls had significantly lower lumbar spine L1-L4 Z scores than the gymnasts.

In conclusion, gymnastics is associated with superior peak bone mass accrual in young males, suggesting a favourable osteogenic environment compared with swimming. The pronounced benefits of this form of weight bearing exercise manifest most evidently during young adulthood relative to pre-puberty, likely mirroring intensified training regimens with maturation.

The bone mineral accrual associated with weight bearing exercise, seem to outweigh the benefits of lean body mass within the swimming group. The findings from this study would encourage recommendation for progressive impact land-based training for swimmers, to counterbalance the time spent in water, (regardless of lean mass) and ensure a more conducive environment for osteogenic loading.

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