

## Original Article

# Mechanical Load-Capacity Models for Bone in Youth – Analysis of Risk Signatures

Marília Marques<sup>1,2</sup>, Paula Bruno<sup>1</sup>, Filomena Vieira<sup>1</sup>, Fátima Baptista<sup>1</sup><sup>1</sup>CIPER, Faculdade de Motricidade Humana, Universidade de Lisboa, Portugal;<sup>2</sup>Hospital Lusíadas Lisboa, Portugal**Abstract**

**Objectives:** to explore associations between mechanical load, expressed by structural (appendicular lean soft tissue index, ALSTI; ALST/trunk fat mass, TrFM); and functional lean mass (handgrip strength, HGS; HGS/body mass) with the mechanical capacity of bone, represented by whole-body bone mineral density less head (WBLH BMD) and arms/legs BMD imbalance. **Methods:** We analysed cross-sectional NHANES data from 5,424 adolescents (10–19 years, both sexes) collected between 2011 and 2020. ALST, TrFM and BMD were determined using whole-body dual-energy X-ray absorptiometry, and HGS was assessed with a dynamometer. All variables were standardised by sex and age group (Z-scores), with Z  $\leq$  -1 indicating low or at-risk values. **Results:** The odds of low WBLH BMD were higher in participants with low ALSTI (girls: OR= 3.9; boys: OR=4.5,  $p < 0.001$ ) or low HGS (girls: OR=3.1; boys: OR=4.5,  $p < 0.001$ ). Boys with low HGS/body mass had 1.8 times higher odds of low arms/legs BMD ( $p = 0.012$ ), while girls with low HGS/body mass had 4.0 times higher odds ( $p < 0.001$ ). **Conclusions:** Both structural and functional lean mass deficits are associated with reduced WBLH BMD and arms/legs BMD imbalance in adolescents. These findings reinforce the importance of lean soft tissue in bone health monitoring.

**Keywords:** Bone Mineral Density, Fat Mass, Handgrip Strength, Lean Body Mass, NHANES**Introduction**

The 'load-capacity model' is a conceptual framework developed to better understand the life-course origins of metabolic diseases<sup>1</sup>. 'Metabolic capacity' refers to physiological characteristics shaped by factors such as nutrition, exercise and growth during pregnancy and infancy, enhancing the ability to maintain metabolic homeostasis and influencing long-term health. In contrast, 'metabolic load' refers to lifestyle factors, such as sedentary behaviour and nutritional status (e.g., high-fat diet), that challenge the capacity for sustained metabolic homeostasis and increase disease risk<sup>2</sup>. The relationship between fat body mass (FBM)

and lean soft tissue (LST) has been explored in the context of metabolic health, considering both markers through the load-capacity model<sup>2</sup>.

Muscles, traditionally regarded as an engine of movement, are now recognised as an endocrine organ that secretes myokines regulating metabolism, inflammation, and cognition<sup>3</sup>. Nevertheless, its fundamental role as the main source of mechanical loading on the skeleton is critical to understanding bone integrity<sup>4</sup>. Fat mass, especially in inactive individuals, also places mechanical load on bones, benefiting bone accrual<sup>5</sup>. However, excessive adiposity places a disproportionate load on weight-bearing bones of the lower limbs compared to the upper limbs, often without a parallel increase in lean tissue or bone strength<sup>6</sup>.

Thus, a bone-specific load-capacity framework is needed to capture how lean and fat mass contribute to skeletal adaptation. Studies have shown a positive correlation between total or appendicular lean soft tissue (ALST) adjusted for height (ALSTI), and whole-body bone mineral content (BMC) or density (BMD)<sup>6,7,8</sup>. Yet, excess body weight, particularly in obesity, is paradoxically associated with higher fracture risk<sup>9</sup>, especially in the upper limbs<sup>10</sup>. This

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Corresponding author: Marília Marques, Departamento Pediatria Hospital Lusíadas Lisboa, Rua Abílio Mendes, 1500 – 458, Portugal  
E-mail: drmariliamarques@hotmail.com

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reflects not only increased impact forces during falls but also biological mechanisms such as altered mesenchymal stem cell differentiation and osteoclast activation that impair bone quality<sup>6,11</sup>.

Generally, leg bones are denser than arm bones due to their role in supporting body weight and performing impact activities<sup>11,12</sup>. Still, bone health in both regions is influenced by shared lifestyle factors such as muscle-strengthening exercise, adequate calcium and vitamin D intake, and overall activity levels<sup>13</sup>. Therefore, examining both weight-bearing (legs) and non-weight-bearing (arms) bones may provide insights into how mechanical loads and body composition jointly shape skeletal health.

Finally, muscle function—commonly assessed by handgrip strength (HGS)—is emerging as an independent marker of both musculoskeletal and general health<sup>14,15,16</sup>. For too long, “well-child visits” have focused primarily on linear growth. Shifting attention to body composition, particularly muscle mass and strength, is essential for a more comprehensive assessment of development and long-term skeletal health<sup>17</sup>. In this context, we aim to investigate the relationship between mechanical load and capacity, focusing on variables related to muscle mass, specifically ALST adjusted for height (ALSTI) and trunk fat mass (ALST/TrFM), as well as muscle function (HGS and HGS/body mass). Bone health is evaluated using WBLH BMD and arms/legs BMD imbalance.

## Material and Methods

### Participants

The study sample included 5,424 (N) participants: 2,818 boys and 2,606 girls aged 10 to 19, representing diverse racial/ethnic backgrounds (Mexican American, other Hispanic, non-Hispanic White, non-Hispanic Black, and other races). These participants were selected from the NHANES (National Health and Nutrition Examination Survey) datasets for the years 2011-2012, 2013-2014, 2015-2016, and 2017-2020. Missing data were handled using listwise deletion. Only cases with complete data on all variables included in the analysis were retained. Participants with self-reported chronic diseases were excluded from the study. The initial NHANES sample comprised 39,156 participants, of whom 33,732 were excluded according to the predefined criteria. NHANES is a program conducted by the Centres for Disease Control and Prevention (CDC) in the United States. It collects data on the health and nutrition of the U.S. population through interviews, physical examinations, and laboratory tests. It is widely used to monitor chronic diseases, nutritional deficiencies, and other public health indicators. Handgrip strength assessments were conducted in 2,889 participants (1,399 girls).

### Body size and somatic maturity

Anthropometric measurements, including height and body mass, were performed by trained health technicians at

the Mobile Exam Centre. Standing height (cm) was measured using a stadiometer, while body mass was assessed using a digital weight scale. Both instruments were electronically linked to the NHANES Integrated Survey Information System (ISIS) for accurate data recording. Participants were weighed in kilograms while wearing a standard Mobile Exam Centre examination gown (comprising a disposable shirt, pants, and slippers). Somatic maturity was assessed by calculating the offset between chronological age and the predicted age at peak height velocity (PHV), using the sex-specific regression equations proposed by Moore et al. (2015)<sup>18</sup>. This measure was expressed as the number of years an individual was advanced or delayed relative to their estimated PHV.

### Body composition and bone density

Appendicular lean soft tissue, total and trunk fat mass, and BMD (WBLH and arms/legs) were measured through a whole-body scan by dual-energy x-ray absorptiometry (DXA, Hologic Discovery model A, Bedford, Massachusetts). Two markers for low lean (excluding bone) were calculated: ALSTI (adjusted for height) and the ALST/TrFM (adjusted for trunk fat mass). These indices were used to minimise categorisation based solely on individual compartments of lean mass or fat mass. Trunk fat mass was specifically chosen due to its well-established association with metabolic syndrome and cardiovascular disease<sup>19</sup>. BMD imbalance between arms and legs was determined by dividing the average BMD of the upper limbs by the average BMD of the lower limbs. DXA scans were performed using Hologic fan-beam densitometers across NHANES cycles, with standardised calibration and quality-control protocols. Daily phantom scans, cross-calibration procedures, and longitudinal monitoring ensured inter-scanner consistency, following NHANES standard operating procedures.

### Handgrip strength

Muscle strength was evaluated using a handgrip dynamometer (Takei Digital Grip Strength Dynamometer, Model T.K.K.5401). Dynamometers were calibrated at the start of each examination stand using standard NHANES protocols. Calibration involved suspending certified weights (11 kg, 21 kg, and 41 kg) from the handle, with acceptable reading ranges defined as  $\pm 2$  kg from the target. Two trained examiners conducted the procedure, and all results were logged as part of routine quality control. The protocol was explained and demonstrated by a qualified examiner, and each participant completed three alternating hand trials, with a 60-second rest between measurements for each hand. The test was performed in a standing position unless physical limitations required otherwise. Participants stood upright, arms by their side, wrists neutral, and the grip aperture was adjusted to fit the hand size. The highest recorded value from the three trials for each hand was used as the final measure of muscle strength.

**Table 1.** Characterisation of female participants, considering the total sample and risk groups based on the appendicular lean soft tissue index and ratio of appendicular lean soft tissue to trunk fat mass, as mean ± SD or n (%).

	ALSTI							ALST/TrFM					
	All Sample n=2606	Low (Z score ≤ 1) n=761	Medium (1 < Z score ≤ 1) n=1299	High (Z score > 1) n=546	p	η <sup>2</sup>		Low (Z score ≤ 1) n=357	Medium (1 < Z score ≤ 1) n=1820	High (Z score > 1) n=429	p	η <sup>2</sup>	
Age, y	14.1 ± 2.9	14.2 ± 2.8	14.1 ± 2.9	14.0 ± 2.9	0.344	0.001	-	13.7 ± 2.8	14.2 ± 2.9	13.9 ± 2.9	<0.001	0.005	L<M
Maturity offset, y	1.7 ± 2.2	1.7 ± 2.2	1.7 ± 2.3	1.8 ± 2.2	0.799	0.000	-	2.6 ± 2.1	1.8 ± 2.2	0.7 ± 2.2	0.001	0.004	L>M>H
Height, cm	156.7 ± 9.0	155.1 ± 9.9	156.6 ± 8.9	159.1 ± 7.6	<0.001	0.050	L<M<H	156.5 ± 8.5	156.7 ± 9.4	156.7 ± 9.0	0.888	0.000	-
Body mass, kg	58.0 ± 18.1	45.8 ± 9.6	56.3 ± 12.7	79.1 ± 20.0	<0.001	0.539	L<M<H	78.1 ± 22.2	56.8 ± 15.4	46.3 ± 10.1	<0.001	0.495	L>M>H
BMI, kg/m <sup>2</sup>	23.3 ± 6.1	18.8 ± 2.5	22.7 ± 3.8	31.0 ± 6.6	<0.001	0.629	L<M<H	31.5 ± 7.0	22.8 ± 4.8	18.6 ± 2.6	<0.001	0.641	L>M>H
BMI category					<0.001	0.593*					<0.001	0.466*	
Underweight	67 (2.6%)	66 (8.7%)	1 (0.1%)	0				0	26 (1.4%)	41 (9.6%)			
Normal	1440 (55.3%)	670 (88.0%)	742 (57.1%)	28 (5.1%)				13 (3.6%)	1053 (57.9%)	374 (87.2%)			
Overweight	541 (20.8%)	24 (3.2%)	403 (31.0%)	114 (20.9%)				60 (16.8%)	467 (25.7%)	14 (3.3%)			
Obese	558 (21.4%)	1 (0.1%)	153 (11.8%)	404 (74.0%)				284 (79.6%)	274 (15.1%)	0			
Fat Mass, kg	20.6 ± 10.1	14.9 ± 4.9	19.4 ± 7.5	31.7 ± 12.2	<0.001	0.459	L<M<H	34.8 ± 11.6	20.0 ± 7.6	11.6 ± 3.4	<0.001	0.729	L>M>H
Fat Mass Index, kg/m <sup>2</sup>	8.3 ± 3.7	6.1 ± 1.7	7.8 ± 2.7	12.4 ± 4.4	<0.001	0.478	L<M<H	14.0 ± 3.9	8.0 ± 2.6	4.6 ± 1.0	<0.001	0.798	L>M>H
Trunk Fat Mass, kg	8.4 ± 5.1	5.6 ± 2.3	7.8 ± 3.8	13.8 ± 6.3	<0.001	0.435	L<M<H	15.9 ± 5.9	8.0 ± 3.7	3.9 ± 1.2	<0.001	0.764	L>M>H
ALST, kg	15.7 ± 4.2	12.3 ± 2.3	15.5 ± 2.8	20.8 ± 4.0	<0.001	0.637	L<M<H	18.1 ± 5.0	15.4 ± 4.0	15.0 ± 3.3	<0.001	0.135	L>M, H
ALSTI, kg/m <sup>2</sup>	6.3 ± 1.3	5.1 ± 0.5	6.3 ± 0.6	8.2 ± 1.1	<0.001	0.803	L<M<H	7.3 ± 1.5	6.2 ± 1.2	6.0 ± 0.9	<0.001	0.211	L>M, H
ALST/TrFM, kg/kg	2.3 ± 1.0	2.5 ± 0.9	2.4 ± 1.1	1.8 ± 0.9	<0.001	0.117	L, M>H	1.2 ± 0.2	2.1 ± 0.6	4.1 ± 0.8	<0.001	0.883	L<M<H
WBLH BMD, g/cm <sup>2</sup>	0.861 ± 0.112	0.803 ± 0.103	0.865 ± 0.104	0.930 ± 0.100	<0.001	0.158	L<M<H	0.866 ± 0.107	0.860 ± 0.111	0.857 ± 0.120	0.478	0.002	-
Arms BMD, g/cm <sup>2</sup>	1.308 ± 0.155	1.236 ± 0.156	1.316 ± 0.142	1.390 ± 0.139	<0.001	0.122	L<M<H	1.299 ± 0.145	1.308 ± 0.153	1.316 ± 0.172	0.309	0.003	-
Legs BMD, g/cm <sup>2</sup>	2.052 ± 0.275	1.903 ± 0.247	2.059 ± 0.251	2.242 ± 0.245	<0.001	0.185	L<M<H	2.097 ± 0.268	2.048 ± 0.273	2.031 ± 0.287	0.002	0.005	L>M>H
Arms/legs BMD	0.64 ± 0.04	0.65 ± 0.04	0.64 ± 0.04	0.62 ± 0.04	<0.001	0.07	L>M>H	0.62 ± 0.04	0.64 ± 0.04	0.65 ± 0.04	<0.001	0.041	L<M<H
HGS, kg <sup>1</sup>	49.7 ± 11.9	44.1 ± 10.2	49.8 ± 11.1	57.9 ± 11.5	<0.001	0.163	L<M<H	50.3 ± 12.2	49.8 ± 12.0	49.1 ± 11.6	0.557	0.001	-
HGS/Body mass, kg/kg <sup>1</sup>	0.9 ± 0.2	1.0 ± 0.2	0.9 ± 0.2	0.8 ± 0.2	<0.001	0.164	L>M>H	0.7 ± 0.1	0.9 ± 0.2	1.1 ± 0.2	<0.001	0.366	L<M<H

ALSTI, appendicular lean soft tissue index; ALST, appendicular lean soft tissue; TrFM, trunk fat mass; BMI, body mass index; WBLH, whole body less head; BMD, bone mineral density; HGS, handgrip strength; L, low; M, medium; H, high. <sup>1</sup> n=1399. \*Cramer's V. Welch's ANOVA was reported instead of the one-way ANOVA whenever the assumption of homogeneity of variances was violated (Levene's test, p < .05). Reported values correspond to Welch's F.

**Table 2.** Characterisation of male participants, considering the total sample and risk groups based on the appendicular lean soft tissue index and ratio of appendicular lean soft tissue to trunk fat mass, as mean ± SD or n (%).

	ALSTI							ALST/TrFM						
	All Sample n=2818	Low (Z score ≤1) n=663	Medium (1< Z score ≤1) n=1585	High (Z score >1) n=570	p	η <sup>2</sup>		Low (Z score ≤1) n=557	Medium (1< Z score ≤1) n=1771	High (Z score >1) n=490	p	η <sup>2</sup>		
Age, y	14.2 ± 2.9	14.3 ± 2.9	14.2 ± 2.9	14.3 ± 2.8	0.638	0.000	-	14.2 ± 2.8	14.2 ± 2.9	14.2 ± 2.8	0.893	0.000	-	
Maturity offset, y	0.5 ± 2.2	0.4 ± 2.3	0.5 ± 2.2	0.7 ± 2.1	0.057	0.005	-	0.4 ± 2.3	0.5 ± 2.2	0.7 ± 2.1	0.077	0.001	-	
Height, cm	163.9 ± 13.2	160.8 ± 14.4	163.9 ± 13.1	167.3 ± 11.3	<0.001	0.059	L<M<H	165.3 ± 12.0	163.2 ± 13.5	164.8 ± 13.7	<0.001	0.014	L>M	
Body mass, kg	63.1 ± 21.6	48.3 ± 12.9	61.3 ± 16.3	85.4 ± 24.5	<0.001	0.486	L<M<H	85.3 ± 24.6	58.9 ± 17.2	53.3 ± 14.1	<0.001	0.412	L>M>H	
BMI, kg/m <sup>2</sup>	23.1 ± 6.1	18.3 ± 2.6	22.4 ± 4.0	30.1 ± 6.6	<0.001	0.617	L<M<H	30.7 ± 6.3	21.7 ± 4.1	19.2 ± 2.7	<0.001	0.590	L>M>H	
BMI category					<0.001	0.509*					<0.001	0.505*		
Underweight	103 (3.7%)	101 (15.2%)	2 (0.1%)	0				0	72 (4.1%)	31 (6.3%)				
Normal	1599 (56.7%)	540 (81.4%)	984 (62.1%)	75 (13.2%)				25 (4.5%)	1139 (64.3%)	435 (88.8%)				
Overweight	498 (17.7%)	19 (2.9%)	376 (23.7%)	103 (18.1%)				104 (18.7%)	371 (20.9%)	23 (4.7%)				
Obese	618 (21.9%)	3 (0.5%)	223 (14.1%)	392 (68.8%)				428 (76.8%)	189 (10.7%)	1 (0.2%)				
Fat Mass, kg	17.1 ± 10.2	11.4 ± 4.5	15.9 ± 7.8	27.2 ± 13.4	<0.001	0.413	L<M<H	32.2 ± 10.6	14.7 ± 5.6	8.9 ± 2.0	0.000	0.745	L>M>H	
Fat Mass Index, kg/m <sup>2</sup>	6.3 ± 3.5	4.4 ± 1.6	5.9 ± 2.8	9.7 ± 4.5	<0.001	0.400	L<M<H	11.7 ± 3.2	5.5 ± 1.9	3.2 ± 0.5	0.000	0.810	L>M>H	
Trunk Fat Mass, kg	6.8 ± 5.0	4.2 ± 2.1	6.2 ± 3.8	11.5 ± 6.7	<0.001	0.383	L<M<H	14.4 ± 5.3	5.5 ± 2.5	3.0 ± 0.8	0.000	0.746	L>M>H	
ALST kg	20.6 ± 6.7	15.9 ± 4.7	20.3 ± 5.5	26.9 ± 7.1	<0.001	0.454	L<M<H	23.3 ± 7.4	19.7 ± 6.4	20.7 ± 6.2	<0.001	0.098	L>M<H	
ALSTI, kg/m <sup>2</sup>	7.5 ± 1.6	6.0 ± 0.9	7.4 ± 1.1	9.4 ± 1.6	<0.001	0.659	L<M<H	8.3 ± 1.8	7.4 ± 1.3	7.5 ± 1.6	<0.001	0.148	L>H>M	
ALST/TrFM, kg/kg	4.0 ± 1.9	4.3 ± 1.4	4.1 ± 2.0	3.2 ± 2.0	<0.001	0.086	H<L, M	1.7 ± 0.4	3.9 ± 1.2	6.9 ± 1.0	0.000	0.927	L<M<H	
WBLH BMD, g/cm <sup>2</sup>	0.902 ± 0.151	0.822 ± 0.135	0.906 ± 0.141	0.983 ± 0.150	<0.001	0.241	L<M<H	0.905 ± 0.133	0.893 ± 0.153	0.929 ± 0.160	<0.001	0.019	M<H	
Arms BMD, g/cm <sup>2</sup>	1.421 ± 0.234	1.318 ± 0.218	1.426 ± 0.218	1.529 ± 0.244	<0.001	0.175	L<M<H	1.410 ± 0.223	1.413 ± 0.235	1.463 ± 0.239	<0.001	0.007	H>L, M	
Legs BMD, g/cm <sup>2</sup>	2.163 ± 0.367	1.965 ± 0.333	2.171 ± 0.342	2.370 ± 0.353	<0.001	0.132	L<M<H	2.202 ± 0.325	2.134 ± 0.369	2.222 ± 0.392	<0.001	0.028	L, H>M	
Arms/legs BMD	0.659 ± 0.042	0.67 ± 0.041	0.66 ± 0.040	0.65 ± 0.044	<0.001	0.088	L>M>H	0.64 ± 0.04	0.66 ± 0.04	0.66 ± 0.04	<0.001	0.046	L<M, H	
HGS, kg <sup>1</sup>	65.6 ± 22.7	55.8 ± 20.3	65.8 ± 21.8	76.0 ± 22.8	<0.001	0.088	L<M<H	67.1 ± 21.7	64.2 ± 22.7	69.3 ± 23.3	0.003	0.008	M<H	
HGS/Body mass, kg/kg <sup>1</sup>	1.1 ± 0.3	1.1 ± 0.2	1.1 ± 0.2	0.9 ± 0.3	<0.001	0.188	L>M>H	0.8 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	<0.001	0.660	L<M<H	

ALSTI, appendicular lean soft tissue index; ALST, appendicular lean soft tissue; TrFM, trunk fat mass; BMI, body mass index; WBLH, whole body less head; BMD, bone mineral density; HGS, handgrip strength; L, low; M, medium; H, high. <sup>1</sup> n=1490. \*Cramer's V. Welch's ANOVA was reported instead of the one-way ANOVA whenever the assumption of homogeneity of variances was violated (Levene's test, p < .05). Reported values correspond to Welch's F.

**Table 3.** Associations between Z-scores of mechanical capacity and mechanical load, stratified by sex, unadjusted (A) and adjusted for somatic maturity (B).

	Girls				Boys			
	A WBLH BMD	B WBLH BMD	A arms/legs BMD	B arms/legs BMD	A WBLH BMD	B WBLH BMD	A arms/legs BMD	B arms/legs BMD
ALSTI	0.544**	0.580**	- 0.304**	- 0.312**	0.555**	0.564**	- 0.242**	- 0.293**
ALST/TrFM	- 0.075**	- 0.047	0.218**	0.219**	- 0.044*	0.033	0.150**	0.138**
HGS	0.492**	0.526**	- 0.079*	- 0.077*	0.529**	0.509**	- 0.046	- 0.052*
HGS/Body Mass	- 0.206**	- 0.144**	0.354**	0.353**	- 0.108**	- 0.043	0.277**	0.280**

*ALSTI, appendicular lean soft tissue index; ALST, appendicular lean soft tissue; TrFM, trunk fat mass; WBLH, whole body less head; BMD, bone mineral density; HGS, handgrip strength. \*p < 0.05; \*\*p < 0.001.*

## Statistical Analysis

Descriptive statistics (mean and standard deviations or absolute frequency and percentages) were used to summarise the characteristics of the variables. The ALSTI was standardised (Z-scores) based on reference ranges for body composition indices<sup>20</sup>; the ALST/TrFM was standardised using the sample as a reference. Both variables were standardised by sex and age. Z-scores  $\leq -1$  were considered indicative of low (L) mechanical load; Z-scores between -1 and 1 represented medium (M) load; and Z-scores  $> 1$  were classified as high (H) mechanical load.

One-way ANOVA was used to compare each of the study variables between the L, M, and H groups based on both the ALSTI Z-scores and ALST/TrFM Z-scores. In each case, Levene's test was applied to assess the homogeneity of variances, and Welch's ANOVA was used when this assumption was violated. Post-hoc comparisons were performed using Scheffé's or Games-Howell's tests, depending on the outcome of the ANOVA or Welch's ANOVA. Eta squared was used as the effect size for ANOVA. Effect size for the Welch ANOVA was estimated using an adapted formula for eta squared, based on the F-statistic and degrees of freedom. This approach provides an approximate measure of explained variance under heteroscedasticity. Additionally, the chi-square test for independence was used to compare the prevalence of BMI categories across the groups. Cramér's V was used to assess effect size.

WBLH BMD was standardised (Z-scores) using reference ranges for bone mineral density<sup>21</sup>, while arms/legs BMD was standardised using the sample as a reference. Handgrip strength and the handgrip strength-to-body mass ratio we used were standardised according to the reference ranges provided by Correia and colleagues<sup>22</sup>. All variables were standardised by sex and age.

Pearson's correlation coefficient was calculated to evaluate the association between mechanical capacity

markers (WBLH BMD, arms/legs BMD), and mechanical load variables (ALSTI, ALST/TrFM, HGS, HGS/body mass), both expressed as Z-scores.

Logistic regression was applied to analyse the effect of mechanical load variables (ALSTI, ALST/TrFM, HGS, HGS/body mass) on the likelihood of identifying a risk signature in the mechanical capacity markers (WBLH BMD or arms/legs BMD). Binary logistic regression models were built using the stepwise forward conditional approach, adding variables one by one based on statistical significance. As a result, only predictors that met the inclusion criteria remained in the final model. For these analyses, dummy variables were generated based on the Z-scores, classifying individuals into a risk group (Z-scores  $\leq -1$ ) or a non-risk group (Z-scores  $> -1$ ). In addition to odds ratios, predicted probabilities of low WBLH BMD and arms/legs BMD imbalance (Z-score  $\leq -1$ ) were generated from the logistic regression models. Using the SPSS "Save" function, predicted values (probabilities and group membership) were calculated and plotted to visualise the probability of outcomes across risk categories of handgrip strength and handgrip strength/body mass.

All statistical analyses were carried out separately by sex. Data analysis was performed using IBM SPSS Statistics, version 29.0 (IBM Corporation, Armonk, NY, USA). Significance was set at  $p < 0.05$ .

## Results

Descriptive statistics are presented in Tables 1 and 2 for girls and boys, respectively. These tables compare the impact of low, medium, and high mechanical load, according to the Z-scores for ALSTI and ALST/TrFM.

Both girls and boys with low mechanical load, as indicated by ALSTI Z-scores, had lower values for height, BMI, fat mass index (FMI), WBLH BMD, and arms and legs BMD, as well as lower handgrip strength. However, they displayed

**Table 4.** Logit coefficients of the binary logistic regression model for low BMD as a function of low appendicular lean soft tissue and handgrip strength.

Model A: Z-score of WBLH BMD $\leq 1$				
Girls	B	SE	p-value	OR (95% CI)
ALSTI (risk)	1.370	0.142	<0.001	3.935 (2.980, 5.195)
ALST/TrFM (risk)	-	-	-	-
HGS (risk)	1.132	0.181	<0.001	3.103 (2.178, 4.420)
HGS/Body Mass (risk)	0.495	0.206	0.016	0.609 (0.407, 0.912)
Constant	1.587	0.094	<0.001	0.205 (0.170, 0.246)
Boys	B	SE	p-value	OR (95% CI)
ALSTI (risk)	1.493	0.149	<0.001	4.450 (3.320, 5.964)
ALST/TrFM (risk)	-	-	-	-
HGS (risk)	1.504	0.182	<0.001	4.502 (3.203, 6.427)
HGS/Body Mass (risk)	0.465	0.204	0.023	0.628 (0.345, 0.937)
Constant	1.680	0.090	<0.001	0.186 (0.155, 0.224)
Model B: Z-score of arms/legs BMD $\leq 1$				
Girls	B	SE	p-value	OR (95% CI)
ALSTI (risk)	0.575	0.176	0.001	0.563 (0.399, 0.795)
ALST/TrFM (risk)	-	-	-	-
HGS (risk)	-	-	-	-
HGS/Body Mass (risk)	1.380	0.157	<0.001	3.975 (2.922, 5.408)
Constant	1.570	0.095	<0.001	0.208 (0.173, 0.250)
Boys	B	SE	p-value	OR (95% CI)
ALSTI (risk)	1.098	0.313	<0.001	0.333 (0.181, 0.616)
ALST/TrFM (risk)	0.877	0.231	<0.001	2.404 (1.530, 3.779)
HGS (risk)	-	-	-	-
HGS/Body Mass (risk)	0.590	0.235	0.012	1.805 (1.138, 2.863)
Constant	2.373	0.120	<0.001	0.093 (0.078, 0.112)

SE, standard error; OR, odds ratio; CI, confidence interval. ALSTI, appendicular lean soft tissue index; ALST, appendicular lean soft tissue; TrFM, trunk fat mass; WBLH, whole body less head; BMD, bone mineral density; HGS, handgrip strength. Models were fitted using the stepwise forward conditional method; variables not included in the final model are indicated by blank cells.

higher values for arms /legs BMD and handgrip strength adjusted for body mass.

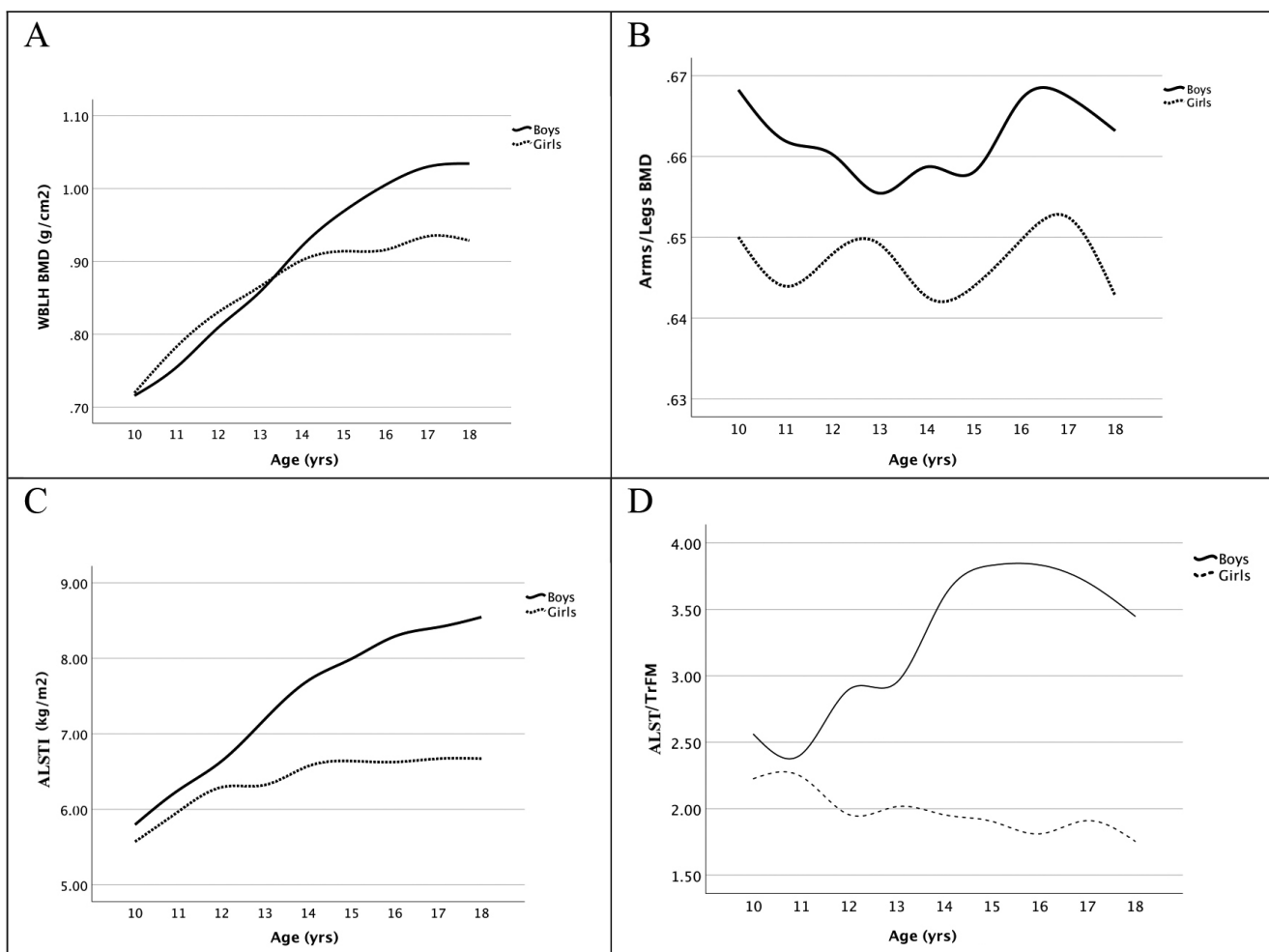
Inversely, girls and boys with low mechanical load based on ALST/TrFM Z-scores  $\leq -1$  demonstrated higher values for BMI, FMI, ALSTI, and lower arms/legs BMD, along with lower handgrip strength when adjusted for body mass.

Figure 1 presents four panels showing variations in selected bone variables reflecting mechanical capacity (WBLH BMD and arms/legs BMD) and muscle variables reflecting mechanical load (ALSTI, ALST/TrFM). These graphs illustrate age-related trends, with a focus on growth and development patterns in the study sample. Greater variations are observed in boys compared to girls, with more linear trends in isolated variables (WBLH BMD, ALSTI), and non-linear patterns in ratio variables (arms/legs BMD,

ALST/TrFM). Notably, lower values in the ratio variables coincide with the age of peak height velocity (11-12 years in girls and 13-14 years in boys).

In both sexes, positive correlations were found between ALSTI and handgrip strength with WBLH BMD, and negative correlations with arms/legs BMD (when significant), both before and after adjustment for somatic maturity (Table 3). In contrast, ALST/TrFM and handgrip strength adjusted for body mass were negatively associated with WBLH BMD and positively associated with arms/legs BMD. These associations remained stable after adjustment for somatic maturity, reinforcing the robustness of the findings.

Table 4 presents the logit coefficients of the binary logistic regression model, which assesses low BMD risk as a function of low appendicular lean soft tissue (ALSTI  $\leq -1$ ;



**Figure 1.** Whole body less head bone mineral density (WBLH BMD (A), arms/legs imbalance BMD (B), appendicular lean soft tissue index (ALSTI) (C), and appendicular lean soft tissue to trunk fat mass ratio (ALST/TrFM) (D) by chronological age.

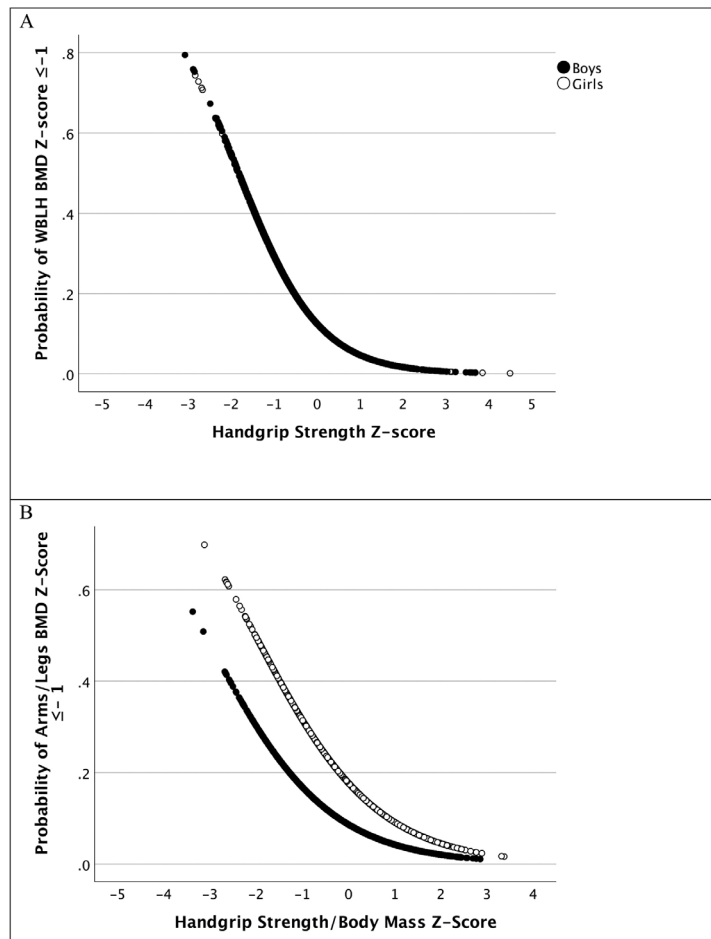
ALST/TrFM  $\leq -1$ ) and low strength (handgrip Z-score  $\leq -1$ ; handgrip/body mass Z-score  $\leq -1$ ).

Girls and boys with low ALSTI had 3.9 times and 4.5 times higher odds, respectively, of low WBLH BMD compared to those with higher ALSTI scores. Similarly, girls and boys with low handgrip strength were at 3.1- and 4.5-times higher odds, respectively, for low WBLH BMD compared to those with higher handgrip strength. Interestingly, girls and boys with low handgrip strength relative to body mass had 0.61 and 0.63-times lower odds, respectively, of low WBLH BMD compared to those with higher handgrip strength relative to body mass.

In terms of arms/legs BMD, girls and boys with low ALSTI had 0.56- and 0.33-times lower odds, respectively, of imbalance compared to those with higher ALSTI. Boys with low ALST/TrFM had 2.4 times higher odds of arms/legs BMD imbalance compared to those with higher ALST/TrFM.

Furthermore, girls and boys with low handgrip strength relative to body mass exhibited 4.0 and 1.8-times higher odds, respectively, of arms/legs BMD imbalance compared to those with higher handgrip strength relative to body mass.

In Table 4, odds ratios are used to compare the strength of association between a risk factor (low lean soft tissue) and an outcome (low BMD) across two groups. In contrast, Figure 2 presents the probability of low BMD occurring versus not occurring within a single group (the total sample). This figure highlights the bone variables and risk factors most strongly associated with both sexes. For both boys and girls, a decrease in handgrip strength Z-scores was linked to an increased probability of low WBLH BMD. Additionally, a greater increase in the probability of arms/legs BMD imbalance was observed in girls compared to boys with lower handgrip strength/body mass Z-scores.



**Figure 2.** Predicted probability of whole body less head bone mineral density (A) and arms/legs bone mineral density imbalance (B) below average (Z-score  $\leq -1$ ) according to handgrip strength and handgrip strength/body mass in boys and girls, respectively. Predicted probabilities were derived from logistic regression models without any covariate adjustment.

## Discussion

This study investigated mechanical load/capacity for bone in youth by examining the risk of decreased capacity (WBLH BMD and arms/legs BMD imbalance) associated with reduced mechanical load (ALSTI, ALST/TrFM, handgrip strength). In this context, we used a Z-score cutoff of  $\leq -1$  as an early risk marker, consistent with previous pediatric research, noting that this approach identifies vulnerability rather than providing a diagnostic classification. Both sexes showed higher odds of low WBLH BMD with low levels of lean mass (ALSTI) and handgrip strength. However, the risks were more pronounced in boys, potentially due to their higher ALSTI and muscle strength compared to girls<sup>23</sup>. For girls, low handgrip strength, was associated with higher odds of low WBLH BMD. Also, girls with low handgrip strength

adjusted for body mass had higher odds of an arms/legs BMD imbalance. This suggests that muscle function may be more relevant than tissue structure in screening bone health risks in girls.

The risk signatures highlighted in this study suggest a strong relationship between WBLH BMD and ALSTI or handgrip strength and between arm/legs BMD imbalance and ALST/TrFM or handgrip strength/body mass. These relationships were influenced by BMI, with ALSTI and handgrip strength Z-scores  $\leq -1$  more prevalent in leaner individuals. In contrast, ALST/TrFM and handgrip strength/body mass Z-scores  $\leq -1$  were more common in overweight or obese individuals. The inverse association observed between low HGS/body mass and low WBLH BMD likely reflects the mechanical loading advantage of excess body weight. Adolescents with overweight or obesity often

exhibit reduced relative strength (low HGS/body mass Z-scores) but simultaneously present higher bone accrual due to greater mechanical load, which may explain the apparently protective association for WBLH BMD. This pattern underscores the importance of considering body composition phenotypes when interpreting muscle–bone relationships.

Previous studies have identified two phenotypes that are indicative of sarcopenia risk in otherwise healthy young individuals: phenotype I characterized by low LSTI and BMI along with low handgrip strength, and phenotype II, characterized by low lean body mass/fat body mass and high BMI and fat body mass index, also associated with low handgrip strength when adjusted for body mass<sup>15</sup>. In the present study, we found that phenotype I is associated with low WBLH BMD, whereas phenotype II is correlated with greater BMD imbalance between the arms and legs. This finding aligns with previous literature that links type I sarcopenia risk phenotype with decreased WBLH BMD<sup>24,25</sup>. However, there is limited evidence regarding the association of type II sarcopenia risk phenotype with increased BMD imbalance between arms and legs<sup>24</sup>.

Because pubertal maturity could potentially confound these associations, we further examined the impact of maturity status. Correlational analyses adjusted for somatic maturity produced results consistent with the unadjusted models, thereby confirming the robustness of our findings. Since both lean and fat mass indices are affected by and affect pubertal development and bone outcomes, further adjusting logistic models for maturity could lead to over-adjustment and mask true associations. Therefore, logistic models were not adjusted for maturity.

Forearm fractures are common among healthy children<sup>25</sup>, particularly during early adolescence, when bone mineral deposition lags behind growth, leading to a period of skeletal vulnerability<sup>26</sup>. During this time, boys, who experience more rapid growth in both height and leg length than girls, are particularly susceptible to BMD imbalance<sup>27</sup>. Excess body weight or obesity further exacerbates the mechanical load on the skeleton, especially in the upper limbs, where bone density is lower compared to the lower limbs<sup>28</sup>.

While studies have suggested a positive relationship between BMI and BMD in obese individuals, with stronger associations in girls<sup>28,29,30</sup> adipose tissue may have a negative association with BMD once adjusted for lean mass, especially in overweight and obese individuals<sup>31</sup>. Adipose tissue can adversely affect bone health through inflammation, oxidative stress, and the redirection of stem cells toward adipogenesis rather than osteoblastogenesis<sup>32</sup>. Furthermore, high adiposity has been associated with an increased risk of fractures<sup>25</sup> as weaker bones are subjected to greater mechanical forces during falls<sup>33</sup>. As a result, maintaining a healthy body composition during childhood and adolescence is critical for optimising bone health and minimising fracture risk later in life.

Children who fail to develop optimal lean and bone mass by the time they reach adulthood are at a greater risk of

skeletal fragility and osteoporosis as they age<sup>34</sup>. It is now recognised that the origins of osteoporosis can be traced back to early childhood, with 40 to 60% of adult bone mass accumulated during the adolescent years<sup>35</sup>.

Overall, the odds of low WBLH BMD were higher in both boys and girls with low muscle mass or low absolute handgrip strength. However, the odds of low arms/legs BMD were particularly elevated in girls with low relative handgrip strength (handgrip strength normalized by body mass), compared to boys. This suggests that mechanical load on bones may depend more on muscle mass in boys and more on muscle strength in girls. Hormonal differences between sexes may help explain this observation, with testosterone promoting muscle growth and strength in boys, while estradiol, the predominant hormone in girls, plays a more significant role in bone health and fat deposition without promoting muscle hypertrophy as the same extent. Consequently, fat-free mass increases more in boys during adolescence compared to girls<sup>36</sup>.

Considering both sexes, handgrip strength, adjusted or unadjusted for body size, appears to be a more reliable marker of mechanical load on bone health than muscle mass alone<sup>37,38</sup>. This emphasizes the importance of handgrip strength as a screening tool for assessing musculoskeletal health and identifying risks related to bone density.

Our study has several notable strengths. First, it benefits from a large sample size (5,424 participants), which enhances the statistical power and generalizability of the findings. Second, we employed DXA to evaluate body composition, which is considered the gold standard for such measurements, ensuring accuracy and reliability. Finally, to the best of our knowledge, this is the first study to assess the impact of BMD imbalance between the arms and legs in a large adolescent population. However, there are also limitations to consider. Additionally, the absence of information on childhood fractures prevents us from evaluating potential associations between fracture history and BMD imbalance, limiting our ability to explore a complete picture of bone health risks. Another important consideration is the potential methodological differences in body composition adjustments between our dataset and the reference values used for comparison. Specifically, while the NHANES dataset includes adjustments to account for changes in DXA instrumentation over time, the reference values from Zemel and colleagues may not apply the same corrections<sup>20</sup>. This discrepancy could introduce some degree of measurement variation when interpreting lean mass indices. Finally, a more detailed medical history, including the presence of chronic diseases and medication use (e.g., steroids, antidiabetic drugs) would have strengthened our conclusions by allowing a more comprehensive analysis of factors influencing bone and muscle health.

In conclusion, this study shows that low whole-body BMD is significantly associated with low handgrip strength, and that imbalances in BMD between the arms and legs are more frequent in individuals with low handgrip strength relative to body mass. These findings reinforce the close

link between muscle structure, muscle function, and bone health, particularly in young individuals. Promoting adequate muscle mass and strength during childhood and adolescence appears essential to support optimal bone health and reduce susceptibility to future skeletal issues, including fractures and osteoporosis.

#### Ethics approval

The National Center for Health Statistics (NCHS) Research Ethics Review Board (ERB) approved the NHANES study protocol. This secondary analysis used publicly available, de-identified NHANES data; therefore, no additional external ethical approval was required.

#### Consent to participate

Participants provided written informed consent under the original NHANES protocol (with parental consent and child assent for ages 10–17). For this secondary analysis of de-identified data, informed consent was waived.

#### Authors' Contributions

Marília Marques, Paula Bruno, Filomena Vieira, and Fátima Baptista conceived and designed the study. Marília Marques and Paula Bruno performed the statistical analyses. Marília Marques drafted the manuscript. All authors critically reviewed the manuscript and approved the final version.

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