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Original Investigation

Determinants of Forearm Bone Mineral Density among Early Adolescents Female Gymnasts and Swimmers

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Purpose: Bone mineral density (BMD) and bone mineral content (BMC) undergo significant changes during life. Among athletes, skeletal health is one of the key elements determining the length and quality of a sports career.
Methods: This study aims to identify and compare the key determinants of forearm BMD among early adolescent female gymnasts (G), swimmers (S), and a non-training group (N), with a focus on training type, nutritional factors, fracture history, and anthropometric characteristics that may influence bone health during critical periods of growth and development. It examined 45 girls aged 10.70 ± .90 years. BMD and BMC of the forearm in the distal (dis) and proximal (prox) segments were measured by densitometry. Dairy consumption and eating habits were assessed by means of a nutritional interview. Basic somatic measurements were carried out. Somatic maturation status, and puberty rate were determined.
Results: All the analyzed bone parameters were significantly higher in group G compared to S and N (η^2> .14; large effect; P< .001). Significantly more often, BMD below normal was recorded in groups S and N vs G. ANCOVA covariance analysis was used to assess the strength of the relationship between forearm bone parameters and biological variables, nutritional variables, and physical activity. The results of covariance analyses showed that BMD dis was significantly influenced by somatic maturation status, and physical activity (adj. R^2= .65; P< .001). A Similar interaction was shown for BMC prox (adj. R^2= .51; P< .001). BMD prox was significantly influenced by physical activity (adj. R^2= .60; P< .001). A Similar interaction was shown for BMC dis (adj. R^2= .38; P< .01). Z-score was significantly influenced by dairy products (n/day) and physical activity (adj. R^2= .54; P< .001).
Conclusions: Physical activity, especially high-impact gymnastic training, turned out to be the strongest determinant of bone parameters of the forearm in girls.

Keywords: bone mineralization, gymnastics, swimming, nutrition, dairy products, osteogenic index, pubertal age

Introduction

Bone parameters, such as BMD and BMC, undergo significant changes throughout life. Among athletes subject to various training loads, the health of the skeletal system is one of the key elements. Healthy bone tissue, resistant to mechanical loads, determines the length and quality of a sports career.[1-4] A proper diet and nutrient intake are particularly important for the construction of bone tissue, both in the general population and in athletes.[5-7]
The increase in bone length and width is caused by constant modeling and remodeling, which results in the growth of BMD, and an increase in BMC. During puberty, the BMC of the whole-body doubles. The rate of bone growth is temporarily delayed by about 6 months from the peak growth rate. This results in a period of relative non-demineralization, which is why the frequency of bone fractures increases.[8,9]
Athletes at an early age often experience stress injuries to bone epiphyses and apophysis, as well as fractures, which account for 10-25% of injuries. That is why it is so important to diagnose the condition of the skeletal system and early prevention of disorders of quantitative and qualitative bone parameters in athletes.[10-12]
It is well known that nutrients such as protein, calcium, and vitamin D have a positive effect on the condition of bone tissue, but attention should be paid to vitamin D supplementation, especially in autumn and winter or when young athletes train most of the time indoors, without access to sunlight. Vitamin D deficiencies may be associated with impaired muscle function, reduced regenerative capacity, impaired immune and cardiovascular function, poor bone tissue, among other rickets, and an increased risk of bone fractures.[10,13,14] A meta-analysis demonstrated the significant role of dairy products in the diet of children and adolescents in bone health. Dairy product consumption in children and adolescents led to significant increases in both total bone mineral content and areal bone mineral density (aBMD) in multiple skeletal regions (e.g., whole body, femoral neck, spine).[15]
It is well established that adequate calcium intake is crucial for optimal bone mineralization during childhood and adolescence. Cross-sectional data from large population surveys show a positive association between dietary calcium intake and total bone mineral density (BMD) in children and adolescents, indicating that higher calcium consumption is linked with greater bone mass accrual during growth.[10]A study by Harvey et al.[16] on 4-year-old children of both sexes indicates an association of moderate to very intense physical activity and calcium intake of about 966 mg/day with increased hip bone density.[16] A large study from NHANES showed a significantly positive association between calcium intake and total BMD in children and adolescents aged 8–19 years, suggesting that higher calcium intake promotes better bone mineralization.[17] Therefore, in addition to the level and type of physical activity, the diet

should also be analyzed. Taken together, these findings indicate that optimal bone health during growth is determined not only by adequate nutritional intake but also by the level, type, and mechanical characteristics of physical activity. However, to date, the results of research on the effect of training on bone mineralization are inconclusive. The type of physical activity performed is important for the health of bone tissue. On the other hand, studies indicate a significant positive effect of systematic training on BMC and BMD in regions of interest (ROIs) and concern large-scale sports disciplines, such as team sports or individual sports, among others, athletics.[18-20] On the other hand, the results of some studies have not shown a positive effect,[21] and have even shown an increased risk of osteopenia and fatigue fractures in various ROIs in athletes.[22] To better contextualize the importance of mechanical loading patterns in young athletes, recent work by Dhahbi highlights how advances in biomechanics contribute to optimizing sports performance, reducing injury risk, and shaping adaptive musculoskeletal responses, thereby strengthening the rationale for examining sport-specific loading environments such as gymnastics and swimming.[23] In the bone mineral study of sports among adolescents analyzed the BMD of the lower limbs and spine in swimmers, basketball players, and non-swimmers was analyzed, indicating the lowest BMD values in the group of swimmers.[2]

In a systematic review and meta-analysis, the authors suggest that team sports such as rugby, basketball, volleyball, handball, and football have moderate to large effects on BMD and BMC. In addition, handball and football increased both BMD and BMC, while rugby only increased BMC. The authors clearly emphasized that there is currently insufficient evidence to show the superiority of any type of athletic training that improves bone health in adults.[24]

Bone health and nutrition are key aspects of diagnosing relative energy deficiency risk assessment in sport (REDs), which captures a variety of health problems resulting from physiological and/or psychological disorders of the body resulting from low energy availability (LEA).[25] REDs is common among both men and women who practice various sports at different levels and can result in serious health consequences, including a significant reduction in bone mineralization.[26] Another study indicates that LEA occurs in 22-58% of adolescent and young adult female athletes, almost 48% have menstrual disorders, and about 23% have low BMD. The group of subjects included athletes of sports acrobatics, ballet, contemporary dance, and synchronized swimming of various ages.[27]

Another study attempted to evaluate the effect of LEA on BMD and trabecular microarchitecture in adolescent female athletes, including 10 gymnasts aged 12-15 years. Significant correlations were found between the BMD of the whole body and the BMD of the lumbar spine with somatic features, especially with body weight. Energy availability was not significantly correlated with bone parameters in this study. However, the authors themselves emphasize the need to expand research in this area on larger samples and with the inclusion of multifaceted analyses of BMD determinants.[28]

Additionally, research indicates that sex hormones ($P< .001$) and bone mineral density (women: $P< .05$) were significantly lower in non-menstruating (37%) and low-testosterone female athletes (40%; 15.1 ± 3.0 nmol/L), and bone injuries were ~4.5-fold more common in non-menstruating and low-testosterone female athletes compared to others. Categorization of men and women using Triad or REDs tools showed that higher-risk groups had significantly lower levels of triiodothyronine (Female and male triad and REDs: $P< .05$) and a higher number of total fractures (Male triad: $P< .001$; RED-S male and female triad: $P< .01$), as well as a marked, up to 10-fold, higher number of training days lost due to bone injuries in the previous year.[29]

A systematic review of the occurrence of LEA, states that as many as 45% of athletes have LEA, including about 43% female athletes and less than 50% male athletes. In addition, 63% of athletes are exposed to REDs. It has been described that athletes with LEA have reduced run performance, training response, endurance performance, coordination, concentration, judgment, explosive power, and agility compared to athletes with normal energy availability. Studies have found mixed results as to whether LEA increases the risk of injury. However, most studies have shown that athletes with LEA have impaired bone health and a higher risk of skeletal strain injuries.[30] One of the studies indicates that due to the characteristics and specificities of sports and their impact on BMD and BMC, categorization can be made. Sports with a high impact on BMC and BMD include gymnastics, judo, karate, volleyball, and sports characterized by variability in striking forces. This is followed by sports with a medium or difficult to determine impact, such as football, basketball, step aerobics, and non-impact sports. Some sports disciplines were initially considered to be the least osteogenic, such as cycling, swimming, and water polo.[31]

This study aims to identify and compare the key determinants of forearm BMD among early adolescent female gymnasts and swimmers, in comparison with a non-training control group, with a focus on the type of training, nutritional, and anthropometric factors that may influence bone health during critical periods of growth and development.

Methods

Characteristics of the studied groups

The study included 45 Polish pre-pubertal girls aged 10.70 ± .90 years (minimum: 9.00 years; maximum: 12.50 years). The study included two groups with different sports disciplines: gymnastics (G, n= 15, with over 4.50 years of training experience), swimming (S, n= 15, with over 4.00 years of training experience), and a group from the general population not training in any sport discipline (N, n= 15). All the girls in the study were of the same ethnic origin (Caucasian European Origin). The sample was taken from the second stage of the study "Bone mineral status in the athlete population 2021-2025".

A purposive sampling strategy was applied. An invitation to participate in the study was distributed to five schools offering specialized sports programs in artistic gymnastics and swimming to recruit participants representing clearly defined and homogeneous training profiles. After obtaining the consent of their parents/legal guardians and the subjects themselves, the participants were qualified for the measurements. All measurements were carried out in the densitometric and kinanthropometric research laboratory. All measurements were carried out by a single team of specialists using a uniform test protocol. Inclusion criteria: sex, participation in systematic training for at least one year, written consent of the participant and parent/legal guardian, and health condition allowing for DXA testing. Exclusion criteria from the study: contraindications to DXA, lack of consent of the participant and/or caregiver, history of metabolic bone diseases, and concomitant variables known to confound results: rickets in childhood, prematurity, low or extremely low birth weight.[32]

The work described has been carried out by the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. The project was approved by the Bioethics Committee. The studies were conducted according to the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Methods for estimating biological maturation

Due to the interest in understanding differences in biological maturation, numerous methods have been developed to estimate the biological maturation gap relative to chronological age, or to identify the maturational stage of an individual.[33]

In this study, two methods were used to assess biological age. A direct interview was conducted using a questionnaire based on the development of secondary sexual characteristics and age at menarche to determine the stage of pubertal maturation. All girls in the study group were characterized by a prepubertal age, and menarche had not yet occurred. Subsequently, methods based on somatic maturation were used. Somatic maturation estimation methods based on anthropometric measurements are among the most widely used in assessing adolescent athletes due to their low invasiveness, ease of use, applicability in both laboratory and field settings, and the low cost of the required equipment.[34,35] The age of puberty in girls was determined using growth and weight percentile curves depending on chronological age and peak height.[36] Morphological age and puberty rate were assessed and interpreted according to the method proposed by Cameron et al.[37]

Methods for assessing somatic characteristics

All somatic variables were measured according to the guidelines of the International Society for the Advancement of Kinanthropometry (ISAK).[38] All measurements were conducted by a certified anthropometrist with over 15 years of experience. In this study, we calculated the technical error of measurement (TEM). In this study, TEM was less than 1.5%. TEM is a common index used in kinanthropometry to quantify the reliability and precision of measurements, indicating the accuracy of repeated measurements by a single anthropometrist (intra-observer) or by different anthropometrists (inter-observer). While the standard error of measurement (SEM) is a broader statistical concept, TEM is more specifically applied to kinanthropometry to gauge the accuracy of measurements made by anthropometrists. TEM is adopted by the International Society for Standardization Advancement in Kinanthropometry (ISAK) for the accreditation of anthropometrists in Australia.[39]

Body height was measured to the nearest .1 cm using a Seca 264 stadiometer (Seca 216, Seca GmbH & Co. KG, Hamburg, Germany) equipped with Seca 360° wireless technology, a heel positioner, and a Frankfurt plane head positioner to ensure proper alignment. Measurements were taken in the morning, with participants barefoot. Body weight was assessed using the bioelectrical impedance method with the JAWON X-SCAN PLUS II Medical Body Composition Analyzer (Certificate No. EC0197 for medical devices, Gyeongsan-si, South Korea) to the nearest .1 kg. For the DXA measurement procedure, the length of the forearm was measured. The measurement was made with a large spreading caliper (GPM, Zurich, Switzerland) to the nearest .1 cm. Measurements were conducted in the morning, in a fasted state, and without clothing.

Methods of assessing the bone tissue of the forearm

Bone mineral density (BMD in g/cm^2), bone mass content (BMC in g), and Z-score of the non-dominant forearm were measured by dual-energy X-ray absorptiometry (DXA). Measurements were made on a Stratec model densitometer (Norland Fort Atkinson, WI, USA) using pediatric software.

The analysis of the data was based on the Z-score (Z-score is obtained by comparison with the reference population on a standard deviation scale obtained from an age-matched reference population). Z-scores were calculated using age, sex, and ethnic reference curves in accordance with recommendations.[40,41] According to the new official ISCD positions updated in 2023, BMD reporting in females before menopause and in males younger than age 50 Z-scores, not T-scores, are preferred. A Z-score of -2.0 or lower is defined as "below the expected range for age," and a Z-score above -2.0 is within the expected range for age.[42]

The measurements were taken in a sitting position, sideways to the densitometer. There were two measurement points: on the proximal section (prox) and on the distal section (dis) of the radius and ulna parts according to the accepted densitometry method. According to the methodology of measuring the forearm by densitometry, two areas were measured: the distal site (radius + ulna) and the general 1/3 proximal site (radius + ulna). Regression statistics were presented for all similar areas of interest (ROIs).[43,44]

In this study, we used DXA, the recommended technology for the clinical measurement of BMD and BMC in children and adolescents. DXA is a radiological method that detects the attenuation of two photon beams of different energies as they pass through soft tissue and bone. It remains the method of choice due to its wide availability, low exposure to ionizing radiation, high precision, rapid scan speed, and access to robust normative pediatric databases.[45]

Assessment of fracture history

Data on the lifetime occurrence of bone fractures were obtained through a structured interview conducted with the parent or legal guardian of each participant. The interview followed a standardized questionnaire developed for pediatric musculoskeletal research and included detailed questions on (1) the number of fractures sustained throughout life, (2) the exact anatomical location of each fracture, (3) the circumstances and mechanism of injury (e.g., sport-related trauma, fall from height, low-impact incident), and (4) the type of medical management required (immobilization, surgical treatment, duration of recovery). Parents were additionally asked to provide the approximate age at which each fracture occurred, whether radiographic confirmation had been obtained, and whether the child had experienced repeated fractures at the same or different locations. To minimize recall bias, interviewers used probing questions and chronological reconstruction (e.g., “before school age,” “during early training,” “competitive season”) to help parents identify relevant events. Whenever available, parents were encouraged to refer to medical documentation (e.g., discharge cards, imaging reports), and these records were used to verify fracture history when provided. For analytical purposes, fractures were categorized as high-impact (e.g., collision, fall during apparatus exercises) or low-impact (e.g., fall from standing height), which allowed evaluation of potential differences in bone vulnerability among gymnasts, swimmers, and controls. All interviews were conducted by trained researchers experienced in pediatric and sport-related data collection, ensuring consistency in the interpretation and recording of parental reports. The variable *“Fractures (presence/absence of lifetime)”* used in the analysis referred exclusively to documented fractures that were confirmed either through medical records or verified through a detailed, structured parental interview.

Methods of assessing diet

24-hour recalls and Diet 6.0 software

Dairy consumption and dietary intake were evaluated using a standardized 24-hour nutritional interview, conducted twice according to the recommended methodology by a specialist in sports dietetics[36,47]. One weekday and one weekend day were included, and the two records were averaged to obtain the typical daily intake. During the interviews, participants provided detailed information on the amount and frequency of dairy consumption, the types of dairy products consumed, and the number of meals eaten per day. The intake of energy (kcal/day), calcium (mg/day) and protein (g/day) was assessed, and the results were interpreted in reference to the Estimated Average Requirement (EAR), defining the average requirement for a given population, and the Recommended Dietary Allowance (RDA), defining the intake sufficient for almost all individuals in the group[45]. Quantitative estimations of food portions were supported by the Photo Album of Products and Foodstuffs in Various Sizes developed by the Food and Nutrition Institute[47]. Energy, calcium, and protein intake (g/person/day) were calculated using the Diet 6.0 software, a validated tool commonly applied in nutritional research due to its accuracy, high response rate, and ease of use. This method is widely used in many large-scale nutritional studies due to its advantages of validity, high response rate, and ease.[36,47,49]

Food Frequency Questionnaire (FFQ)

In addition to the two 24-hour quantitative interviews, habitual dietary patterns were assessed using a food frequency questionnaire (FFQ). This instrument collected qualitative and semi-quantitative data on the usual consumption of dairy products and other relevant food groups over the three months preceding the study. The FFQ enabled the evaluation of long-term dietary habits that may not be fully captured by short-term recalls, providing a complementary perspective on participants' nutritional behaviors.

Statistical analysis

All calculations were performed using the Statistica software (v.13.3, StatSoft, USA). The Shapiro-Wilk test verified the normality of the distribution, while the assumption of equality of variance was verified using the Levene test. The reliability coefficient of the measurements was Cronbach's α= .91. To assess differences between the three groups of girls in biometric, somatic, skeletal, and nutritional characteristics, a one-way analysis of variance (ANOVA) was performed. In cases where significant differences were found, post hoc comparisons were conducted using the Bonferroni correction. Effect size was assessed by partial eta squared ($\eta 2$) and classified as no effect= 0 to .039; minimal effect= .04 to .24; moderate effect= .25 to .63; and strong effect= ≥ .64.[50]The chi-square test ($\chi 2$) was used to assess differences in the incidence of low BMD on the forearm and low age %BMD in gymnastics (G), swimming (S), and non-training (N) groups. Cramer's *V* coefficient was used to determine the effect size of the chi-square test (small effect: .1; average effect: .3; large effect: .5).[51] ANCOVA covariance analysis was used to assess the strength of the relationship between forearm bone parameters and biological variables, nutritional variables, and physical activity. The values of the adjusted coefficients of determination *adj.* R^2 are given. The degree of correlation of the predictors was assessed using the variance inflation factor (VIF) collinearity test, taking a not-to-exceed value of 10. Residual analysis was also performed, testing for homoscedasticity using the White test and the degree of correlation of the residuals using the Durbin-Watson test. The effect size was calculated as eta-square ($\eta 2$) (small effect: < .06; average effect: .06 – .14; large effect: > .14).[52-54] The interaction between Z-score and dairy consumption was analyzed using one-way ANOVA. In the case of statistically significant results, post hoc comparisons were performed using Tukey's test. In all analyses, the significance levels were: *P< .05; **P< .01; ***P< .001 (P - P-value).

Results

Table 1 presents a comparative analysis of biometric, somatic, skeletal, and nutritional characteristics, considering the type of sport discipline trained. Several significant intergroup differences were noted. Group G had significantly higher all bone parameters in both sections of the measurement (P< .001; large effect; $\eta 2$> .14) compared to groups S and N, while exhibiting significantly lower body weight and biological age (P< .001; large effect; $\eta 2$> .14). Dietary parameters also showed intergroup differentiation of selected variables. Significantly higher energy intake (kcal/

Table 1. Biometric, somatic, bone, and nutrition characteristics in three groups of girls: gymnastics (G), swimming (S), and the non-training group (N)

Variables	**G (n=15) 1**	**S (n=15) 2**	**N (n=15) 3**	**Significant differences between groups**	***F (P)***	***η2***
	Mean ±SD					
Biometric and somatic						
Age (years)	10.67±.93	10.65±.86	10.81±.90	-	.14 (.868)	-
Somatic pubertal age (years)	9.77±1.31	11.42±.98	11.35±.98	1vs2vs3	10.73 (.000)***	.34
Body Height (cm)	125.34±10.49	135.54±12.78	133.61±17.60	-	.95 (.394)	-
Body Weight (kg)	22.28±3.52	36.18±12.69	39.36±8.55	1vs2vs3	15.05 (.000)***	.42
Bone						
BMD dis. (g/cm^2)	.515±.104	.278±.089	.300±.059	1vs2vs3	34.81 (.000)***	.62
BMC dis. (g)	1.220±.309	.786±.187	.817±.183	1vs2vs3	16.10 (.000)***	.43

BMD prox. (g/cm^2)	.746±.111	.482±.138	.413±.113	1vs2vs3	31.61 (.000)***	.60
BMC prox. (g)	1.600±.203	1.063±.354	.986±.268	1vs2vs3	21.01 (.000)***	.50
Z-score	.817±.169	-.685±.841	-.220±.726	1vs2vs3	21.05 (.000)***	.50
Nutritional						
Energy (kcal/day)	1233.20±313.40	1126.33±175.52	1016.67±153.10	1vs3	3.46 (.041)*	.14
EAR Energy (%)	66.28±16.68	60.63±9.78	54.37±8.50	1vs3	3.58 (.037)*	.15
Protein (g/kg bw)	.87±.23	1.05±.15	1.05±.17	1vs2vs3	4.42 (.018)*	.17
Protein (g/day)	19.33±6.04	38.79±17.59	40.84±9.22	1vs2vs3	14.72 (.000)***	.39
RDA Protein (%)	64.42±20.14	129.30±28.45	136.14±30.74	1vs2vs3	14.72 (.000)***	.39
Calcium (mg/day)	1028.40±212.49	1002.27±136.12	925.67±136.97	-	1.56 (.223)	-
RDA Calcium (%)	79.11±16.34	77.10±10.47	71.21±10.53	-	1.56 (.222)	
Dairy products (n/day)	2.60±1.40	1.60±1.19	1.51±1.22	-	1.72 (.192)	-

Legend to Table 1: BMD– bone mineral density; BMC– bone mineral content; dis– distal part of forearm; prox– proximal part of forearm; EAR- estimated average requirement; RDA- recommended dietary allowance; *F*- Ronald A. Fisher's test; *η2*- eta-squared, effect size; *P*– P-value; levels of significance were: *$P< .05$; **$P< .01$; ***$P< .001$

day) ($P< .05$; average effect; $\eta2= .14$) and EAR Energy (%) ($P< .05$; large effect; $\eta2> .14$) were found in G compared to N. On the other hand, groups S and N were characterized by significantly higher protein intake (g/kg bw) ($P< .05$; large effect; $\eta2> .14$) and protein intake (g/day) ($P< .001$; large effect; $\eta2> .14$) and RDA Protein (%) ($P< .001$; large effect; $\eta2> .14$) in comparison with G (Table 1).

Prevalence below the expected range for age BMD (Z-score), pubertal age category, fractures, and dairy products in diet in gymnastics (G), swimming (S), and in the non-training group (N) is presented in Table 2. A significantly higher incidence of normal Z-score ($P< .01$; average effect; $V= .46$) was observed

Table 2. Prevalence of below the expected range for age BMD (Z-score), low BMD matched for age, pubertal age category, fractures, and dairy products in diet (Chi-square test results).

Variables	G (n=15)	S (n=15)	N (n=15)	χ^2 (*P*) *V*
		%		
Z-score (SD)				
BMD within the expected range for age	100.00	53.30	80.00	9.51 (.003)**
BMD below the expected range for age	0.00	46.70	20.00	.46
Somatic pubertal age relative to chronological age (years)				
Compatible	60.00	73.30	86.70	14.78 (.005)**
Delayed	40.00	0.00	6.70	.41
Fast-tracked	0.00	26.70	6.70	
Fractures (presence/absence of lifetime)				
Yes				
No	66.70	40.00	6.70	11.53 (.003)**
	33.30	60.00	93.90	.51
Dairy products (yes/no in the diet)				
Yes	86.70	60.00	53.30	16.35 (.038)*
No	13.30	40.00	46.70	.43
Type of dairy products (types)				
No dairy products	13.30	40.00	46.70	6.31 (.177)
Only milk	33.30	40.00	26.70	.26
Mix (milk, cheese, yogurt)	53.40	20.00	26.60	

Legend to Table 2: *χ2*- chi-squared test; *P*- P-value, levels of significance were: *$P< .05$; **$P< .01$; ***$P< .001$; *V*- Cramer's V coefficient, the effect size of the chi-square test in group G compared to groups S and N. Only in group G was the Z-score at the level expected for a given age. In group S, on the other hand, the highest percentage of players whose Z-score value was below the expected range for a given age was recorded. A significantly higher incidence of agreement between somatic adolescence and chronological age was found in groups S and N compared to group G (*P*< .01; average effect; *V*= .41). Significantly more frequent fractures in the past were observed in group G compared to groups S and N (*P*< .01; large effect; *V*= .51). Dairy products were significantly more often present in the diet of group G compared to groups S and N (*P*< .05; average effect; *V*= .43) (Table 2).

Relationships between BMD, BMC in the dis and prox parts of the forearm, and biological variables, nutritional variables, and physical activity are presented in Table 3 (results of ANCOVA analyses). Among the significant determinants of bone parameters, the type of physical activity in relation to somatic pubertal age was noted for distal BMD and proximal BMC (*adj.* R^2= .65 and .51). The interactions of these variables explained between 51% and 65% of the variance in bone parameters. However, for proximal BMD and distal BMC, the only significant predictor was physical activity (*adj.* R^2= .60 and .38). Significant predictors influencing the Z-score were the consumption of dairy products (average effect; *P*< .05) in association with the type of physical activity (large effect; *P*< .001). The interaction of these features explained the 54% variability in the Z-score (*adj.* R^2= .54) (Table 3).

Table 3. Relationships between forearm bone parameters and biological variables, nutritional variables, and physical activity (results of ANCOVA analyses).

	BMD dis. (g/cm²)	**BMD prox. (g/cm²)**	**BMC dis. (g)**	**BMC prox. (g)**	**Z-score (SD)**
			***F* (*P*) η^2**		
Somatic pubertal age (years)	6.301 (.017)* .149	2.989 (.092) .077	.295 (.590) .008	4.962 (.032)* .121	.730 (.399) .020
Body weight (kg)	.834 (.367) .023	3.319 (.077) .084	1.424 (.241) .038	1.041 (.314) .028	2.154 (.151) .056
Dairy products (n/day)	2.734 (.107) .071	.679 (.415) .019	.497 (.485) .014	1.325 (.257) .036	4.556 (.040)* .112
Energy (kcal/day)	.234 (.631) .006	.267 (.608) .007	.026 (.874) .001	2.261 (.141) .059	1.876 (.179) .050
Protein (g/kg bw)	.002 (.964) .000	.234 (.632) .006	.461 (.501) .013	.027 (.871) .001	.820 (.371) .022
Calcium (mg/day)	.000 (.994) .000	.088 (.769) .002	.167 (.685) .005	1.816 (.186) .048	1.656 (.206) .044
Physical activity (group)	14.049 (.000)*** .438	15.638 (.000)*** .465	10.173 (.000)*** .361	5.519 (.008)** .235	9.893 (.000)*** .355
F (*P*) *adj.* R^2	11.3 (.000)*** .65	9.14 (.000)*** .60	4.34 (.001)*** .38	6.67 (.000)*** .51	7.40 (.000)*** .54

Legend to Table 3: BMD– bone mineral density; BMC– bone mineral content; dis– distal part of forearm; prox– proximal part of forearm; *F*- Ronald A. Fisher's test; *adj.* R^2- the adjusted R-squared values of determination; $\eta 2$- eta-squared, effect size; *P*- P-value, levels of significance were: **P*< .05; ***P*< .01; ****P*< .001.

The results of two-way ANOVA assessing main effects and interaction of type of physical activity (Factor A) and type of dairy products consumption (Factor B) or number of dairy products in diet per day (Factor C) on Z-score are shown in Table 4. A two-way analysis of variance was conducted to assess the main effects and the interaction in the first model between factor A: type of physical activity and factor B: type of dairy product consumption, concerning the Z-score. Both factors were shown to significantly affect the Z-score but independently of each other. No significant interaction was shown. Model 2 was conducted to assess the main effects and the interaction between factor A: type of physical activity and factor C: number of dairy products consumed, concerning the Z-score. A significant interaction was observed between type of physical activity and number of dairy products in diet per day (*F*= 4.169; *P*= .002; η^2= .485), suggesting that the effect of one factor on Z-score depends on the level of the other factor. The η^2 value for the interaction indicates a large effect size (η^2> .14), emphasizing the importance of the interplay between these two variables (Table 4).

Figure 1 illustrates the impact of the type of dairy product consumed on Z-score (A) and the impact of the number of dairy products consumed on the Z-score (B). The Z-score analysis

Table 4. Two-way ANOVA assessing main effects and interaction of type of physical activity (Factor A) and type of dairy products consumption (Factor B) or number of dairy products in diet per day (Factor C) on Z-score.

Source of Variation			**Model 1**		
	SS	***MS***	***F***	***P-value***	***η2***
Factor A	9.661	4.830	17.292	.000***	.490
Factor B	6.346	3.173	11.358	.000***	.387
A x B Interaction	1.491	.373	1.334	.276	.129
Error	10.056	.279	-	-	-
Source of Variation			**Model 2**		
	SS	*MS*	*F*	*P-value*	*η2*
Factor A	3.797	3.797	21.652	.000***	.411
Factor C	5.795	1.932	11.015	.000***	.516
A x C Interaction	5.117	.731	4.169	.002**	.485
Error	5.436	.175	-	-	-

Legend to Table 4: Factor A: G vs. S vs. N; Factor B: no dairy products vs. only milk vs. mix (milk, cheese, yogurt); Factor C: 0 dairy products per day vs. 1 vs. 2 vs. 3 vs. 4; *SS*– sum of squares; *MS*– mean square; *F*– F-statistic; *P*– P-value; levels of significance were: *$P< .05$; **$P< .01$; ***$P< .001$; η^2 – eta squared, effect size.

showed that the results varied depending on the type of dairy products consumed. The girls who did not consume any dairy products had the lowest average Z-score, close to -.40, while the greatest effect on the Z-score was observed in the respondents who consumed a mix of milk and other dairy products .6. The variation analysis indicated a significant effect of the type of dairy products consumed on the Z-score. The group consuming a mix of milk and dairy products achieved significantly higher results than the group consuming only milk and the group not consuming any dairy products (*P*< .001) (Figure 1, A).

The B part of Figure 1 showed the impact of the number of dairy products consumed on the Z-score (B). The analysis showed a statistically significant effect. Detailed Post-hoc analysis indicates significance between no dairy products (Z-score< -.3), one dairy product/day (Z-score< -.02) and two dairy products/day (Z-score< .1) compared to three dairy products/day (Z-score> .8); (*P*< .001) and between no dairy products vs two dairy products/day (*P*< .001). The highest Z-score value was obtained by people who consumed three dairy products during the day. The number of dairy products consumed changes to a Z-score (Figure 1, B).

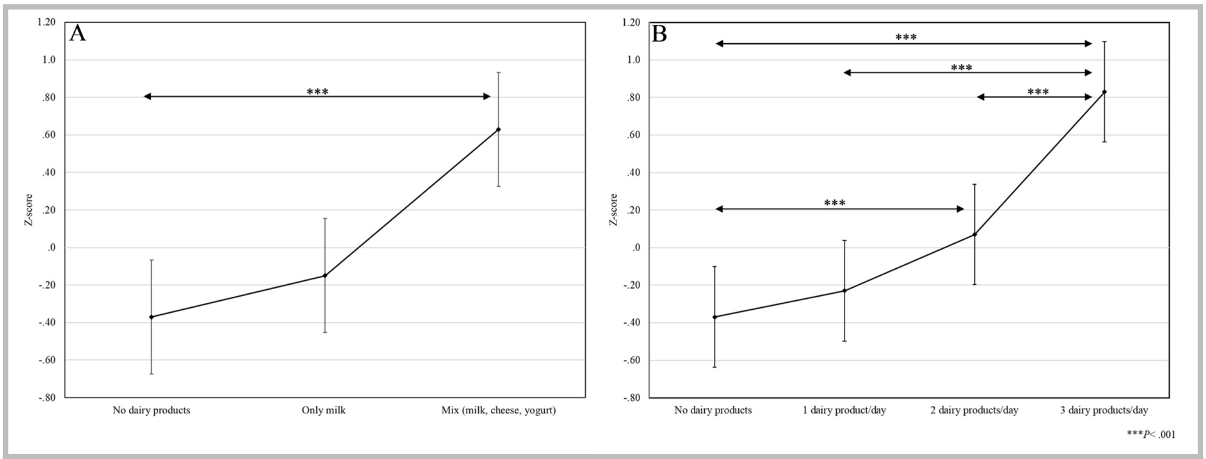

Figure 1. The impact of different types of dairy product consumption on Z-score (A) (one-way ANOVA results; $F(2.36)= 11.358$; P< .001; vertical lines ± .95CI- confidence intervals) and the impact of number of dairy products consumptions of Z-score (B) (one-way ANOVA results; $F(3.31)= 11.015$; P< .001; vertical lines ± .95CI- confidence intervals).

Discussion

Physical activity, its type, intensity, and duration, has an impact on the skeletal system of every athlete, both recreational and professional. In competitive sports, care should also be taken to educate young athletes, coaches, and parents about proper eating patterns and the consequences associated with REDs or LEA, which, among girls, can lead to problems related to puberty and delayed or absent menstruation.[29]

BMD and BMC are subject to high variability during ontogeny, so the right choice of physical activity from an early age is important due to the decreasing level of physical activity in late adolescence. Promoting high-impact sports may be especially important for optimal bone development in the final years before peak bone mass (PBM) is reached.[31,55,56]

A comparative study of girls training rhythmic gymnastics (RG) aged 9-13 years and their non-training peers, concerning the effect of weight-bearing exercises performed during gymnastic training, showed that in girls training RG before menarche, positive skeletal adaptation, especially of the cortical bone, and a positive response of bone geometry associated with prolonged duration of exercise. In addition, the two groups were comparable in height and chronological age, yet training showed a positive relationship with cortical BMC, surface area, and thickness

regardless of chronological age.[57]
In our study, G girls showed a delayed biological age in relation to their peers S and N and calendar age, and significantly higher bone parameters.
Nutrition and supplementation have a significant impact on bone health, especially the consumption of dairy products, which provide protein, calcium, and phosphorus, which are the main building blocks of bones, [5] and their consumption during childhood and adolescence leads to higher PBM.[6]
The WHO does not specify a specific number of dairy products but recommends including them in the context of a balanced diet. The U.S. Dietary Guidelines for Americans 2025–2030 recommend 3 servings per day of low-fat or fat-free dairy products (e.g., milk, yogurt, cheese) in the "Healthy U.S.-Style Pattern", about 2 glasses of milk. Substitute products (e.g. fortified soy drinks) may be considered equivalent, but the dairy plant must be fortified with calcium, D, and B_{12}. The Nordic Nutrition Recommendations 2023 recommend a dairy intake: 350–500 g per day. Low-fat products (milk, yogurt, cheese) are preferred to protect against cardiovascular diseases, while ensuring an adequate supply of calcium, iodine, and B_{12}.[58, 59]
The Polish recommendations of the National Institute of Public Health, in line with the population group from this study, recommend the consumption of at least 3-4 servings of milk or dairy products per day, especially in the teenage years.[46]
The results of this study show that none of the groups G, S, and N meet the conditions of the average portion consumption of dairy products, but group G has the highest percentage of dairy product intake per day. The consumption of dairy products in the diet was declared by 86.7% in group G, 60% in group S, and 53.3% in group N. The type of dairy products in the diet is also important for bone health. According to the Polish recommendations, milk contains about 3.3 g of protein per 100 g of product, while the value of protein in yoghurt, cottage cheese, and cheese ranges between 4.3-26.1 g of protein per 100 g of product.[46]
In this study, 40% of group S, 33.3% of group G, and 26.7% of group N declared milk consumption. The mix of milk with other dairy products was declared by 53.4% of group G, and only 20% of group S. The lowest percentage of respondents who did not consume any dairy products was declared in group G (13.3%). On the other hand, there was a high, alarming percentage of female athletes (40% and more) in groups S and N who did not consume dairy products in their diet.
Higher quantitative and qualitative consumption of various dairy products in group G is associated with higher BMD and BMC values compared to groups S and N, in which lower values of the examined bone parameters were observed. This may be associated with a less balanced diet and a poorer range of products responsible for bone structure and strength.
In addition to the important aspects of diet in bone health, this paper discusses the influence of the type of training and sport discipline on BMD. The available results of assessments of bone health of athletes indicate that there is insufficient evidence on what intensity and length of exercise is required to perform safe osteogenic stimulations.
There are extensive studies that suggest that weight-bearing sports stimulate bone formation compared to weight-relieving sports such as swimming, but there is no detailed data on the duration of training, or the type of exercise used. In the case of some sports disciplines, there are publications on the interaction of the specificity of training, diet and supplementation with bone mineral status.[60,61]
Our research is in line with that of Agostinete et al.[2], due to the highest percentage of low BMD among the subjects from group S. In this study, swimmers had higher BMD prox and BMC prox values than the non-training group. This may be related to the positive effect of water resistance forces acting on the upper limb, especially in the proximal region, which is involved in swimming training more than the distal segment.
Another important aspect of bone health tests in athletes is the risk assessment and incidence of fatigue and stress fractures. The high incidence of such fractures in athletes compared to the general population is indicated by publications from the Web of Science, PubMed, EBSCO, SPORTDiscus, MEDLINE and Cochrane Library databases included in the systematic review by Sun et al.[62]
An analysis of high-quality studies of athletes qualified for this review showed that sports activities that involve constant and strong movements significantly contribute to the risk of developing stress fractures. This mechanism can be caused by continuous stress on the bone, leading to micro-damage that can accumulate over time, in combination with a number of other factors such as low bone mass, poor bone mineralization, or the athlete's body type. Among the sports disciplines where more than 70% of athletes suffered fatigue fractures, football and long-distance athletics were mentioned.[62]
The conducted research indicates, despite the small size of the group and the young age of the players, that in group G, fractures have already been experienced by nearly 70% of the respondents and 40% of the athletes from group S, which may be associated with the above-mentioned repeated movements in training. Repeatedly performing the same movement sequences may weaken bone structure, which can lead to stress fractures. This type of fracture is not related to poor bone mineralization and is not associated with low BMD and BMC. Group G had the highest bone parameters, so the highest incidence of fractures is not due to bone mineralization problems but to the specific nature of the training and its repetitive movement patterns, defining the fractures as stress fractures. Identifying specific risk factors for these types of fractures and how they interact with each other is critical to developing effective strategies for injury prevention and treatment.
Understanding the sport-specific mechanical loading patterns is essential for interpreting physiological adaptations in young athletes. Recent reviews highlight the role of biomechanics and motion analysis in injury prevention, emphasizing how detailed assessment of movement patterns can inform training strategies and reduce injury risk.[63] These insights support our findings by suggesting that the distinctive mechanical demands of gymnastics and swimming likely contribute to the observed differences in bone mineral density and skeletal adaptation. Incorporating biomechanical analyses into future studies could further elucidate the mechanisms by which sport-specific loading shapes musculoskeletal development.
In this study, interestingly, although the gymnastics group exhibited the highest bone mineral density (BMD), they also showed the highest lifetime prevalence of fractures, which at first glance may appear paradoxical. This apparent discrepancy can likely be explained by the nature of these fractures, many of which were trauma-related and not necessarily indicative of bone fragility. Young gymnasts, especially girls, are exposed to sport-specific mechanical stresses and falls that increase the risk of such injuries, even in the presence of robust bone mass. This interpretation aligns with epidemiological studies in youth athletes, which demonstrate that high-intensity training and sport-specific activities contribute substantially to fracture risk independent of bone density [64]. These findings underscore the

importance of distinguishing between fractures resulting from mechanical trauma and those related to low bone strength when interpreting skeletal health in young athletes.

Our research has limitations, such as a small sample size, due to the fact that it is very difficult to encourage parents to allow their children to participate in the study because of the DXA measurement. In our opinion, parents have concerns about DXA radiation testing, despite assurances that the ionising radiation dose is low, harmless to health regardless of age, and provides information about bone tissue condition. In addition, although the ANCOVA models showed relatively high adjusted R^2 values, additional diagnostic checks (VIF, residual analysis, and sensitivity testing) indicated that the models were not overfitted and remained stable. Nevertheless, given the modest sample size, these results should be interpreted with appropriate caution.

Practical applications

The findings of this study underscore the critical importance of comprehensive bone health assessment in young athletes, with particular attention to dietary factors influencing bone mineralization. Early identification of nutritional deficiencies through dietary analysis enables timely interventions, which are essential for optimizing bone development and reducing the long-term risk of bone demineralization. This, in turn, contributes to the prevention of low-impact fractures and other skeletal complications in later life.

The integration of dual-energy X-ray absorptiometry (DXA) or comparable densitometric techniques into routine diagnostics can facilitate the identification of skeletal regions particularly susceptible to stress-related injuries. Such localized bone health assessments allow for targeted modifications in training programs, incorporating exercises aimed at enhancing bone strength and mechanical resilience.

Given these considerations, it is recommended that sports clubs, school-based athletic programs, and training center's implement structured nutritional support for youth athletes. This should include not only individualized dietary oversight but also educational initiatives aimed at parents and caregivers regarding evidence-based nutritional practices for children and adolescents. Furthermore, school curricula should incorporate education on protein-rich food consumption and promote the importance of balanced nutrition for musculoskeletal health. Physical education (PE) programs should be expanded to include exercises with osteogenic potential, focusing on skeletal loading and muscle-strengthening activities that support optimal bone development during the growth period.

Conclusion

In conclusion, girls training in gymnastics had statistically higher BMD and BMC values in both studied regions of the forearm (proximal and distal) compared to girls training in swimming and their peers participating only in PE program classes. The type of physical activity performed may be an important factor among children and adolescents and could serve as a predictor of bone status. In addition, the consumption of dairy products with a high protein content, such as cheese or yogurt, is positively associated with bone mineralization. Considering both factors, osteogenic physical activity and a protein-rich diet, among athletes may be important in the context of preventing bone injuries, including reducing the risk of premature termination of a sports career and the development of osteopenia or osteoporosis later in life.

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Informed Consent Statement

Informed consent was obtained from all study participants and their parents/legal guardians.

Ethical Committee approval

The work described has been carried out by the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. The project was approved by the Bioethics Committee of the National Institute of Public Health and the National Institute of Hygiene in Warsaw, Poland (protocols number 1/2021 and 2/2025).

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The authors have no conflicts of interest to declare.

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Author-s contribution

Conceptualization W.P.; methodology A.K.; software W.P. and A.K.; formal analysis W.P.; investigation W.P.; resources W.P.; data curation A.K.; writing - original draft preparation W.P. and A.K.; writing review and editing W.P. and A.K.; supervision A.K.; project administration W.P. All authors have read and agreed to the published version of the manuscript.

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