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Association between frequency of energy drink consumption and bone tissue quality in Slovak young adults

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Bone mineral density, physical activity, energy drinks, quantitative ultrasound, bioimpedance analysis

Abstract

Background The study of bone health in younger individuals is less explored than in older populations but may offer insights into preventing future bone conditions.

Objectives This study analyzes the link between bone quality and energy drink consumption while considering factors like physical activity and body composition.

Sample and Methods The sample comprised 911 Slovaks, male and female, aged 18–30 (21.53 ± 2.27). Bone mineral density was measured using a quantitative ultrasound device (Sunlight MiniOmni™), yielding speed of sound (SOS; m/s) data. Body composition variables, including Lean Body Mass (LBM; kg) and Percent Body Fat (PBF; %), were assessed with the bioimpedance analyzer InBody 770. Additional behavioural factors were gathered via a questionnaire based on the WHO Steps 2014.

Results Sex was found to be a significant predictor of SOS [$F(11,899 = 4.01)$, $p < 0.001$, $R2 = 0.047$], with females showing higher SOS than males ($p < 0.001$), whereas physical activity ($p = 0.594$) was not a significant predictor. Although energy drink consumption did not show a direct impact on SOS according to the Saint Nicholas House Analysis (SNHA), it was a significant predictor in those who drank 1–2 days/week ($p = 0.009$) and those who drank less than once a month ($p=0.023$) with these individuals exhibiting lower SOS than non-consumers, thus poorer bone tissue quality.

Conclusion In summary, energy drinks consumed 1–2 days/week and less than once a month are associated with bone tissue quality in young adults, albeit not directly posing a potential adverse effect on bone health.

Take-home message for students Sex and lifestyle significantly influence bone tissue in young adults. While energy drink consumption is linked to lower bone quality, no direct causal relationship was found. Recognizing these factors early may help guide strategies for preventing future bone health issues. Further research on nutritional impacts is needed.

Abbreviations

BCM : Body cell mass
BC : Body composition
BMI : Body mass index
BMD : Bone mineral density
DBP : Diastolic blood pressure
DXA : Dual-energy X-ray absorptiometry
EDC : Energy drink consumers
Non-EDC : Energy drink non-consumers
FFM : Fat free mass
FFMI : Fat free mass index
FM : Fat mass
FMI : Fat mass index
LBM : Lean body mass
mPhM : Medium-intensity physical activity
mQUS : Multisite quantitative ultrasound
MM : Muscle mass
PBF : Percent body fat
QUS : Quantitative ultrasound
SMM : Skeletal muscle mass
SOS : Speed of sound
SBP : Systolic blood pressure
WHR : Waist-to-hip ratio

Introduction

Energy drink use is becoming increasingly common worldwide, especially among the younger generations and athletes (Kaur et al. 2022; Reissig et al. 2009). It was reported in the university student population that those who performed physical activity were significantly more likely to consume energy drinks (Pavlovic et al. 2023); this behaviour was also found in association with short sleep duration and high intake of fast food and snacks (Nuss et al. 2021; Poulos and Pasch 2015). The ingredients and concentrations in such drinks vary broadly by brand and product; however, most share a few common ingredients, such as caffeine, taurine, sucrose, and B vitamins (Higgins et al. 2018; Higgins et al. 2010). Concerns have been raised about their safety owing to potential adverse effects, namely sleeping disorders, anxiety, cardiovascular events, and seizures (Puupponen et al. 2023; Somers and Svatikova 2020). As a result of the variable composition of this drink category, most of the studies analyze the effect on the bone of the individual ingredients, such as caffeine, which can be up to 141mg in a 250ml can (Nowak and Jasionowski 2015) and not on energy drinks in general.

Caffeine appears to affect bone density at a molecular level by intensifying osteoclastic differentiation and acting as a non-specific antagonist of adenosine receptors, inhibiting bone formation and promoting bone resorption (Berman et al. 2022; Liu et al. 2011). To the best of our knowledge, although studies have examined the effects of carbonated soft drinks and cola beverages on bone tissue, there appears to be a lack of research specifically on the impact of energy drinks on bone tissue in young adults. Animal studies have provided some insights into these effects. A study on 24 adult female albino rats using soft drinks like Coca-Cola and 7up over four months revealed adverse effects on bone tissue (AL-Hadrawy and Jawad 2022). The findings demonstrated a significant increase in serum calcium and inorganic phosphorus levels and a decrease in magnesium and vitamin D3 concentrations after two weeks. Additionally, soft drinks were found to have detrimental impacts on the bone's histological structure. Research has also noted significant increases in alkaline phosphatase, osteocalcin, and bone sialoprotein, which are responsible for disrupting the balance between new bone formation and bone resorption. Furthermore, Birlik et al. (2017) investigated the effects of energy drinks on the expansion of the median palatal suture in the maxilla of twenty male rats. Ten of these rats were administered a daily dose of 3.57ml/kg of an energy drink primarily containing caffeine and taurine. However, the study found that consuming small amounts of caffeine daily did not influence bone formation. Studies show mixed results when transitioning to human research. Similarly, heel bone density measured using dual-energy X-ray absorptiometry (DXA) in 740 girls aged 12 and 15 years was lower in carbonated soft drink consumers (McGartland et al. 2003). In contrast, Conlisk and Galuska (2000) did not find a significant interaction between coffee and caffeine-containing drinks (coffee, tea, and caffeinated cola) and bone density measured in the lumbar spine and femoral neck with DXA in 177 women aged 19–26.

Additionally, bone fragility and fracture risk assessments are mainly evaluated via bone mineral density (BMD) measured using DXA. However, recent studies indicate that DXA-derived BMD inadequately predicts fracture resistance in both adults and children (Docaj and Carriero 2024), with multisite quantitative ultrasound (mQUS) emerging as a non-invasive diagnostic tool that measures bone speed of sound (SOS) to evaluate bone health, being able to identify aspects of bone quality aspects not detectable by DXA, such as elasticity and trabecular microarchitecture (Dane et al. 2008; Kaufman and Einhorn 1993; Weiss et al. 2003). Furthermore, DXA exposes patients to low levels of ionizing radiation, yields higher costs and requires specialized personnel to operate it. Whereas the disadvantages of QUS include the reduced spatial resolution compared to DXA and inconsistent results due to variations in operator technique and measurement locations.

Energy drink consumption by athletes is a topic of great interest due to the possible impacts on their health and performance. Studies indicate that athletes who drink energy drinks experience improved focus and performance during both anaerobic and aerobic exercises (Correa-Rodríguez et al. 2018; Tambalis 2022). While some studies suggest that consuming energy drinks in moderate amounts can improve athletic performance (Gutiérrez-Hellín and Varillas-Delgado 2021), high-dose intake may result in reduced performance and increased oxidative stress (Wang et al. 2022). Moreover, research indicates that individuals who engage in physical activities, including young adults, generally adopt healthier dietary patterns. A study by Watts et al. (2018) found that young adults who regularly practised yoga consumed more fruits and vegetables, drank fewer sugar-sweetened beverages, ate fewer snack foods and fast food, and participated in more hours of moderate-to-vigorous physical activity. Furthermore, Mazurek-Kusiak et al. (2021) observed that active individuals exhibited superior eating habits compared to their sedentary counterparts. Physical activity's effect on BMD varies mainly on the type of sport, intensity, and frequency; however, as a result of sedentary behaviours, there is a reduction of weight-bearing loads on the bone tissue, leading to alterations in bone turnover (McMichan et al. 2021). Therefore, this study aimed to investigate if SOS obtained from QUS depends on energy drink consumption, specifically if lower SOS is observed in those who consume energy drinks compared to those who do not, with adjustments in the regression analysis for behavioural factors such as physical activity and body composition.

Sample and methods

Sample

A sample of 911 young Slovaks (284 males, 627 females), all aged 18 to 30 (21.53 ±

2.27) years, was investigated. The participants were mainly university students recruited via non-random volunteer and convenience procedure at the laboratory of the Department of Anthropology, Comenius University in Bratislava. The Ethics Committee of Comenius University Bratislava, protocol number ECH19021, approved the sample collection and analyses. Written informed consent was given by all participants per institutional Human Investigation Committee guidelines following the Declaration of Helsinki amended in October 2013, after information about the procedures used in the experiments. From the original sample of 1006, those with invalid QUS measurements (n = 58) and missing body composition data were excluded; no other exclusion criteria were applied.

Anthropometric analysis and blood pressure measurement

Anthropometric measurements were obtained by trained anthropologists using internationally recognized methodologies (Lohman et al. 1988). Height was measured precisely to the nearest 0.5cm using a Siber and Hegner anthropometer, with participants positioned upright, with their feet together, against a wall. The integrated weight scale of InBody 770 precisely measured the body mass to the nearest 0.1kg. A tape measure, Seca 201 (Seca GmbH & Co. KG, Germany) was used to obtain hip and waist circumferences with the participants standing upright and relaxed, their feet together, and their arms crossed in front of their chests. Waist circumference was measured at the narrowest part of the abdomen without compressing the tissue at the end of the normal exhalation. The hip circumference was measured by placing a tape measure on the maximum circumference of the buttocks. Body mass index (BMI) is calculated by dividing an individual's body mass (kg) by the square of their height (m2). Waist-to-hip ratio (WHR) is calculated by dividing the circumference of an individual's waist by the circumference of their hips; values less than 0.84 for women and less than 0.89 for men were considered optimal (WHO 2000).

Lastly, blood pressure (mmHg) and heart rate (BPM) were measured with a digital sphygmomanometer (Omron M3) three times; in the present study, the mean value of the three measurements was used (Souchek et al. 1979).

Body composition analysis

Body composition analysis was evaluated with the InBody 770 analyzer (Biospace Co., Ltd., Republic of Korea), which utilizes segmental multifrequency bioelectrical impedance analysis to evaluate body composition by transmitting low-level electrical currents through the body and assessing resistance in various tissues. The instrument evaluates lean body mass (LBM) and fat mass (FM) for the entire body, trunk, and arms in both percentage and kilograms, visceral fat mass in squared centimeters, percent body fat (PBF), skeletal muscle mass (SMM), and fat free mass (FFM) in kilograms. The values expressed as percentages represent the ratio of an individual's body composition measurement to the mean value for subjects of equivalent height and sex, as derived from reference data (Arman 2021). Hurt et al.'s research (2021) compares the Dual-energy X-ray Absorption (DXA) method with the InBody 770 body composition analyzer. The validation studies reveal a high 98% correlation between these two techniques, highlighting the InBody 770 as a dependable substitute for DXA in measuring body composition. Measurements were conducted under controlled conditions to ensure accurate results, with participants refraining from engaging in physical activity for eight hours before the measurement, abstaining from significant water and food intake for three hours prior to the examination, standing barefoot on the pedal plate electrode, and holding the hand electrode at a 15° angle to avoid arm-to-torso contact (National Institutes of Health 1996; Arman 2021).

Bone quality measurement

The BMD data were collected utilizing a quantitative ultrasound device, specifically the Sunlight MiniOmni™ (BeamMed Inc., Israel) on the distal third of the left radius, measured at the midpoint between the elbow at the olecranon process of the ulna and the end of the distal phalanx of the digitus medius, using an ultrasound gel and repeating the measurements three to five times. Based on its operational design, the instrument determines the number of SOS measurements, typically ranging from 3 to 5. The built-in software automatically generates the final results without providing individual measurement data. Before each data collection day, the instrument was calibrated. The instrument measured the SOS [m/s], with higher values associated with increased bone density.

Questionnaire

Data regarding physical activity and energy drink consumption were collected by administering to the participants an extensive self-reporting, standardized and validated questionnaire adapted from the World Health Organization (WHO) STEPS 2016 – instrument version 3.2 (WHO 2016), which focused on medical history, diet, and behaviours such as physical activity. Energy drink, tea, coffee, and sweetened drink use was ascertained by asking the participants how often they consume these beverages; similarly, for physical activity, it was asked how often they practice sports, with the following options as replies: daily, 5–6 days/week, 3–4 days/week, 1–2 days/week, 1–3 days/month, less than once a month, and lastly, not at all. Individuals who reported consuming energy drinks were categorized as energy drink consumers (EDC), regardless of the frequency of the consumption. In contrast, those who indicated they did not consume energy drinks at all were categorized as energy drink non-consumers (non-ECD). A yes or no question evaluated medium and intense physical activity. For medium intensity physical activity, the question was "Do you do any moderate-intensity sports, fitness or leisure activities (e.g., fast walking, swimming, volleyball) for at least 10 minutes that cause your breathing and heart rate to increase?", for intense physical activity "Do you do any intense sports, fitness or recreational activities that cause you to constantly have a major increase in breathing or heart rate (e.g., running, football) for at least 10 minutes?".

Statistics

A p-value threshold of < 0.05 was used to determine statistical significance. Descriptive statistics, including the Student's t-test and Mann-Whitney U test, were used based on the data distribution assessed with the Kolmogorov-Smirnov test. Spearman's rho and Pearson's correlation were used for correlation analysis between continuous variables to establish potential interactions between SOS and health conditions, such as the number of fractures, thyroiditis, Crohn's disease, liver conditions, diabetes type 1, eating disorders, epilepsy, oncological pathologies, and celiac disease; however, no significant correlations were found. Principal component analysis

(PCA) was used to select the most relevant body composition and behavioural variables. Forward linear regression analysis was used to analyze the predictors, such as diastolic blood pressure (DBP), PBF, LBM, physical activity, sex, and energy drink consumption of SOS. St. Nicolas House Analysis (Groth et al. 2019) was used to visualize and detect the interactions among the variables under the study. Chi-square tests and a bar plot were used to investigate the relationship between energy drink consumption and physical activity.

The data were analyzed using jamovi (version 2.3.21) and R (4.4.1 - Package snha (Groth 2023)).

Results

The baseline characteristics of male students divided into EDC (n = 157) and non-EDC (n = 127) are illustrated in Table 1. It includes the bone parameter SOS 4025.59±120.81 (m/s) in EDC and SOS 4028.53±110.92 (m/s) in non-EDC, as well as body composition parameters such as FFM, LBM, SMM, PBF, FM in the arm, LBM in the arm, visceral fat mass, blood pressure, and heart rate. Statistically significant differences between the two groups were observed in the following variables, heart rate ($p = 0.005$), FFM ($p = 0.035$), LBM ($p = 0.048$) and LBM in the arm ($p = 0.032$).

Similarly, baseline characteristics of female students divided into energy drink consumers (EDC; n = 205) and energy drink non-consumers (non-EDC; n = 422) are illustrated in Table 2, including the bone parameter SOS 4050.29 ± 127.41 (m/s) in EDC and SOS 4080.28 ± 104.76 (m/s) in non-EDC as well as body composition parameters, blood pressure, and heart rate. Statistically significant differences between the two groups were observed only in the variable SOS ($p = 0.002$). Nevertheless, the practical significance of this 30m/s variation is unclear, as it falls within the scope of technical variability and may not significantly affect bone health in young, healthy subjects.

Descriptives conducted on the frequency of physical activity show that 50 (5.52%) individuals practised sports daily (SOS 4051.78±102.55m/s), 69 (7.62%) practised 5–6 days/week (SOS 4040.90 ± 110.16m/s), 218 (24.09%) practised 3–4 days/week (SOS 4053.25±138.82 m/s), 336 (37.13%) practised 1–2 days/week (SOS 4054.82 ± 107.93m/s), 95 (10.50%) practised 1–3 days/month (SOS 4074.74 ± 116.75m/s), 37 (4.09%) less than once a month (SOS 4086.05 ± 122.82m/s) and lastly, 100 (37%) not at all (SOS 4054.41 ± 94.14m/s), bone quality however did not show to be significantly affected by the frequency of engagement in physical activity ($p = 0.416$)

In order to reduce the number of variables and capture most of the variance in the data, a PCA was performed (Table 3). This analysis provided five components, the first associated with variables related to skeletal muscle mass (SMM) and LBM but negatively associated with sex (-0.877); although not with the highest value, the sex variable suggests that this component might distinguish between male and female body composition (BC); component two represents FM distribution; component three, mainly associated with diastolic blood pressure (0.858); component four, reflects levels of physical activity and component five, dietary habits.

Energy drink consumption demonstrated variable effects on SOS (Table 4). Significant negative associations were observed in individuals consuming energy drinks 1–2 days per week ($\beta = -0.353$, $p = 0.009$) and less than once a month ($\beta = -0.198$, $p = 0.023$), indicating poorer bone quality in these groups compared to non-consumers. Additionally, sex was a significant predictor of SOS ($\beta = 0.469$, $p < 0.001$), with females showing higher SOS values than males. However, no significant effects were observed for higher consumption frequencies. Among body composition variables, LBM had a positive but non-significant association with SOS ($\beta = 0.632$, $p = 0.114$), while PBF and mPhA also showed non-significant effects. The regression model explained only 4.7% of the variance in SOS (adjusted $R^2 = 0.035$), suggesting that other unmeasured factors likely contribute to bone quality. The T values across predictors indicated variability in their relative contributions, and the Durbin–Watson statistic of 1.700 suggests that residuals exhibited no autocorrelation issues, supporting the validity of the regression model.

Consuming energy drinks 1–2 days per week ($p = 0.009$, $B = -40.949$) and less than once a month ($p = 0.023$, $B = -23.019$) was associated with significantly lower SOS values than non-EDC. Specifically, individuals who consume energy drinks 1–2 days per week exhibit a lower SOS of approximately 40.949m/s compared to non-EDC, while those who consume such beverages less than once a month demonstrate a lower SOS of approximately 23.019m/s (Figure 1 and 2).

These findings suggest that even moderate or infrequent consumption of energy drinks may be negatively associated with bone tissue. Conversely, other categories of energy drink consumption, as well as

Table 1 Baseline body composition and bone quality characteristics of energy drink consumers and non-consumers of male Slovak young adults

	Energy drink consumers (n = 157)		Energy drink non-consumers (n = 127)		
	Mean	SD	Mean	SD	p
Age	21.93	2.26	22.44	2.51	0.073
Height (cm)	180.87	7.10	180.15	7.18	0.396
Body mass (kg)	78.98	11.94	77.45	15.71	0.353
SOS (m/s)	4025.59	120.81	4028.53	110.92	0.833
BMI (kg/m^2)	24.10	3.05	23.81	4.22	0.496
WHR	0.81	0.05	0.80	0.04	0.415
SBP (mmHg)	133.71	13.32	132.22	12.70	0.339
DBP (mmHg)	70.29	8.82	71.60	8.40	0.202
Heart rate (BPM)	77.83	14.03	73.34	12.24	0.005*
FFM (kg)	64.72	8.08	62.55	9.12	0.035*
LBM (kg)	61.44	7.60	59.54	8.46	0.048*
SMM (kg)	36.92	4.78	35.85	5.88	0.093
PBF (%)	17.19	6.76	17.75	7.49	0508
FM arm (%)	116.87	104.75	136.22	194.96	0.286
LBM arm (%)	104.10	10.69	101.33	10.81	0.032*
Visceral FM (cm^2)	58.54	36.40	60.02	42.05	0.751

* Marks statistical significance $p < 0.05$
Abbreviations: n, number of individuals; SD, standard deviation; SOS, Speed of sound; BMI, Body mass index; WHR, Waist to hip ratio; SBP, Systolic blood pressure; DBP, Diastolic blood pressure; FFM, Fat free mass; LBM, Lean body mass; SMM, Skeletal muscle mass; PBF, Percent body fat; FM, Fat mass.

PBF, LBM, and medium-intensity physical activity (mPhA), did not show statistically significant effects on bone quality in our study sample. Therefore, while specific categories of energy drink consumption were significant predictors, the overall impact of energy drinking, physical activity, DBP and BC on bone health was relatively modest, as indicated by the low R^2 (0.047) and adjusted R^2 (0.035) values. After dividing EDC consumers into two groups, the first one encompassing regular consumers (n = 42, SOS 4045.19 ± 128.83m/s) thus those who declared to drink daily, 5–6 days/week and 3–4 days/week and a second group of medium to low-frequency consumers (n = 318, SOS 4042.00±124.98) which included those who drank 1–2 days/week, 1–3 days/month and less than once a month, no significant differences in SOS values were found (p = 0.747).

Since most energy drinks contain caffeine, coffee consumption was analyzed; however, no statistically significant differences in SOS (p = 0.477) were found between coffee consumers (n = 694, SOS 4055.36 ± 119.31m/s) and non-consumers (n = 217, SOS 4061.79 ± 105.02m/s); similar results to energy drink consumption were also observed when coffee drinking was studied by dividing the coffee drinkers into regular consumers (n = 478, SOS 4059.50 ± 118.70m/s) and medium to low-frequency consumers (n = 216, SOS 4046.50 ± 120.50m/s) p = 0.746.

To visualize the relationships between the variables more effectively, a St. Nicholas House analysis was conducted (Figure 3).

Table 2 Baseline body composition and bone quality characteristics of energy drink consumers and non-consumers of female Slovak young adults

	Energy drink consumers (n = 205)		Energy drink non-consumers (n = 422)		
	Mean	SD	Mean	SD	p
Age	21.11	2.11	21.31	2.19	0.265
Height (cm)	167.38	6.09	166.44	6.17	0.073
Body mass (kg)	61.75	11.40	60.28	10.67	0.114
SOS (m/s)	4050.29	127.41	4080.28	104.76	0.002*
BMI (kg/m^2)	22.00	3.70	21.74	3.54	0.384
WHR	0.75	0.07	0.74	0.05	0.086
SBP (mmHg)	118.01	14.61	117.36	11.69	0.546
DBP (mmHg)	69.86	7.09	69.64	8.50	0.753
Heart rate (BPM)	79.75	13.09	79.95	13.09	0.858
FFM (kg)	43.91	5.31	43.22	5.40	0.133
LBM (kg)	41.57	5.07	40.95	4.82	0.136
SMM (kg)	24.05	3.17	23.69	3.03	0.166
PBF (%)	27.72	7.37	26.84	7.26	0.154
FM arm (%)	126.07	76.04	118.06	68.44	0.186
LBM arm (%)	95.55	9.64	95.16	8.99	0.615
Visceral FM (cm^2)	78.80	41.40	73.43	38.08	0.108

* Marks statistical significance $p < 0.05$

Abbreviations: n, number of individuals; SD, standard deviation; SOS, Speed of sound; BMI, Body mass index; WHR, Waist to hip ratio; SBP, Systolic blood pressure; DBP, Diastolic blood pressure; FFM, Fat free mass; LBM, Lean body mass; SMM, Skeletal muscle mass; PBF, Percent body fat; FM, Fat mass.

The results revealed that sex was a central node, exhibiting significant correlations with LBM (r = -0.78) and PBF (r = -0.35). Energy drink consumption did not demonstrate a direct, significant correlation with SOS, not being directly connected but connected indirectly through sex, suggesting sex-related differences in energy drink use and SOS. Additionally, mPhA failed to correlate significantly with any of the variables under study.

A chi-square test was used to investigate whether the previously observed results could be explained by the hypothesis that

Table 3 Principal component analysis of body composition, anthropometric, and lifestyle variables

Component Loadings						
	Component					
	1	2	3	4	5	Uniqueness
SMM (kg)	0.981					0.0298
LBM (kg)	0.980a					0.0239
FFM (kg)	0.976					0.0357
Sex	-0.877a					0.2148
Height (cm)	0.839					0.2869
Body mass (kg)	0.718	0.563				0.0283
LBM arm (kg)	0.671					0.4775
Waist circumference (cm)	0.643	0.584				0.1050
WHR	0.491					0.6486
Visceral FM (cm^2)		0.976				0.0476
PBF (%)	-0.547	0.884b				0.0556
FM arm (kg)		0.876				0.1905
BMI (kg/m^2)	0.377	0.830				0.0777
Hip circumference (cm)	0.412	0.714				0.2077
DBP (mmHg)			0.858c			0.2383
Heart rate (BPM)			0.716			0.4312
SBP (mmHg)	0.539		0.580			0.3114
Medium PhA				0.809d		0.3496
Intense PhA				0.790		0.3652
Coffee drinking						0.9089
Sweetened drinks					0.667	0.5337
Tea drinking	0.305					0.8029
Energy drinks					0.662e	0.5178

Note. 'oblimin' rotation was used

Component 1: Lean body mass and sex
Component 2: Fat mass
Component 3: Heart and blood pressure
Component 4: Physical activity
Component 5: Energy drinks
Abbreviations: SMM, Skeletal muscle mass; LBM, Lean body mass; FFM, Fat free mass; WHR, Waist to hip ratio; FM, Fat mass; PBF, Percent body fat; BMI, Body mass index; DBP, Diastolic blood pressure; SBP, Systolic blood pressure; PhA, Physical activity.

regular EDC (those who drink daily, 5–6 days/week and 3–4 days/week) are more physically active, suggesting that these individuals might use energy drinks to boost performance and sustain energy during exercise, which could subsequently have a beneficial effect on bone density (Table 5). The results obtained indicate no statistically significant association between the frequency of energy drink consumption and engagement in mPhA (p = 0.507).

Although the results were not statistically significant, it was observed that most individuals who performed mPhA did not consume energy drinks at all. Similar results were observed in individuals who refrained from engaging in mPhA, with the majority reporting no consumption of energy drinks at all. Among the inactive participants, compared to those physically active, a greater proportion reported daily consumption (Figure 4).

The same hypothesis, thus whether regular EDC (those who drink daily, 5–6 days/week and 3–4 days/week) are more physically active, was also tested using a chi-square test on those who performed intense physical activity (Table 6). The results show no statistically significant association between the frequency of energy drink consumption and engagement in high-intensity physical activity, similar to mPhA (p = 0.507).

Table 4 Association of SOS with sex, blood pressure, body composition, physical activity and energy drink consumption frequency of young Slovaks

Dependent variables	Predictors	Unstandardised B	Standardised β	p	R2	Adjusted R2
SOS (m/s)	Sex (Female—Male)	54.411	16.193	<0.001*	0.047	0.035
	DBP (mmHg)	-0.463	0.478	0.333		
	PBF (%)	0.238	0.548	0.664		
	LBM (kg)	0.999	0.632	0.114		
	mPhA (No—Yes)	-4.390	8.225	0.594		
	Energy drink consumption frequency: Daily—None	-53.135	30.979	0.087		
	Energy drink consumption frequency: 5–6 days/week—None	-7.530	38.438	0.845		
	Energy drink consumption frequency: 3–4 days/week—None	6.749	25.495	0.791		
	Energy drink consumption frequency: 1–2 days/week—None	-40.949	15.594	0.009*		
	Energy drink consumption frequency: 1–3 days/month—None	-11.367	13.436	0.398		
	Energy drink consumption frequency: <once a month—None	-23.019	10.084	0.023*		

* Marks statistical significance p < 0.05. Abbreviations: B, beta coefficient; p, value of statistical significance (linear regression analysis, forward method); R2, coefficient of determination; SOS, Speed of sound; LBM, Lean body mass; PBF, Percent body fat; DBP, Diastolic blood pressure; SBP, Systolic blood pressure; mPhA, Physical activity of medium intensity.

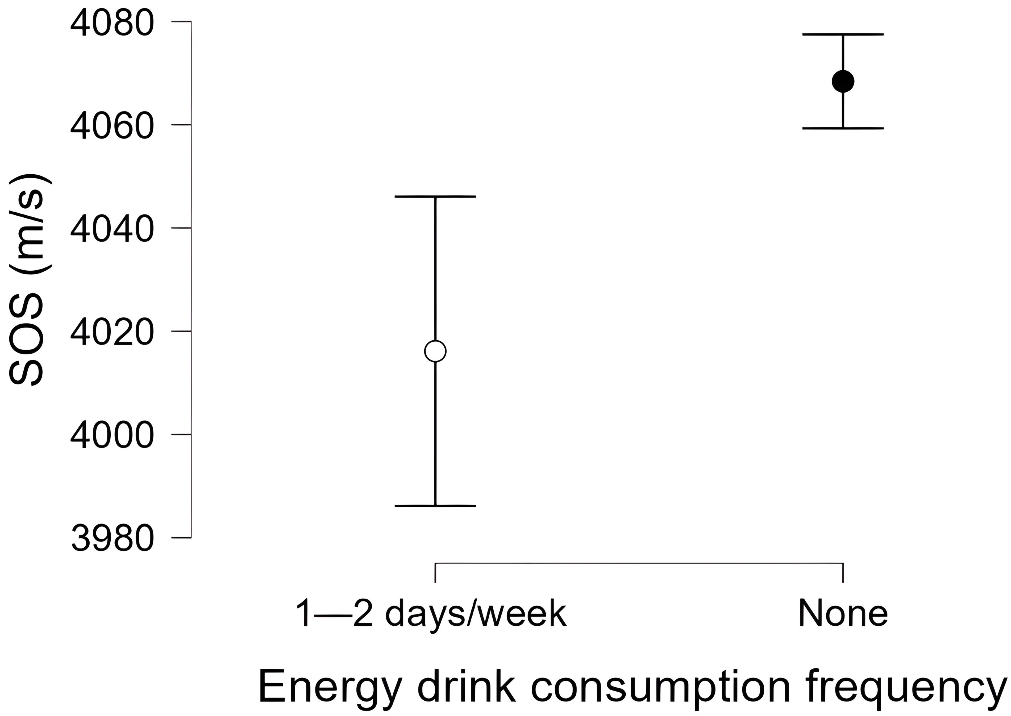

Figure 1 Comparison of energy drink consumption frequency impact, 1–2 days/week versus non-consumers on SOS, Abbreviations: CI, confidence interval; SOS, speed of sound (Created using JASP version 0.19.3)

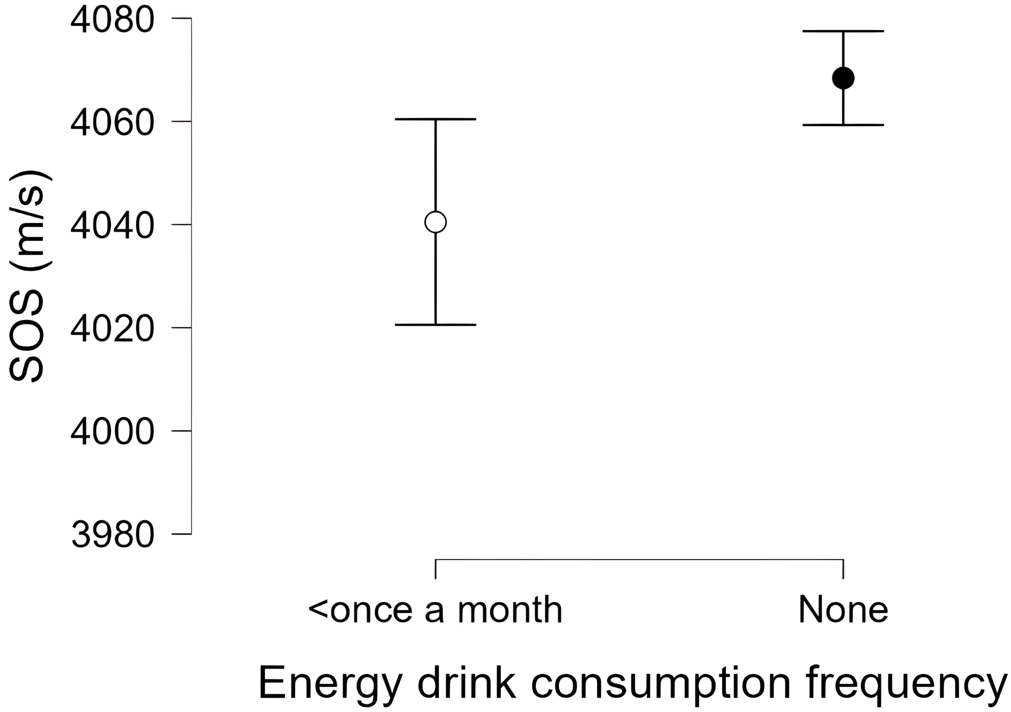

Figure 2 Comparison of energy drink consumption frequency impact, less than once a month versus non-consumers on SOS, Abbreviations: CI, confidence interval; SOS, speed of sound (Created using JASP version 0.19.3)

Discussion

Energy drinks association with bone health

This research offers important insights into how energy drink intake might affect bone quality, utilizing SOS as a non-invasive indicator of skeletal health. A notable strength of this investigation is its concentration on young university students, a group often overlooked in studies concerning bone

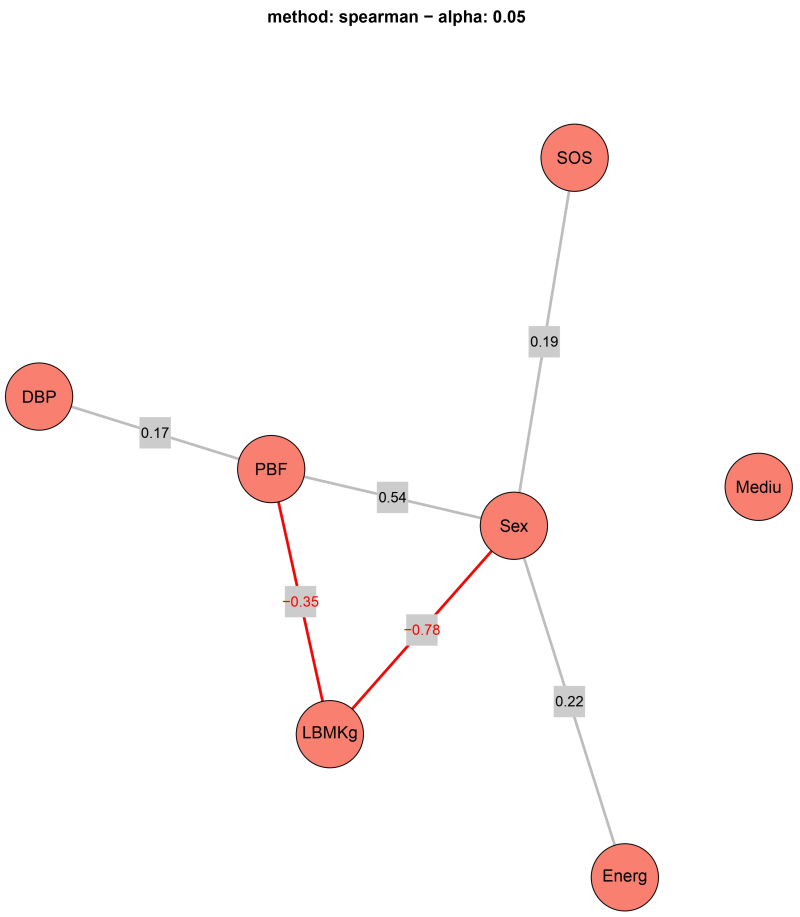

Figure 3 St. Nicholas House graph of variables influencing bone density concerning energy drink consumption of young Slovaks. Abbreviations: DBP, Diastolic blood pressure; PBF, Percent body fat; LBMKg, Lean body mass; Energ, Energy drink consumption frequency; Mediu, Medium intensity physical activity; SOS, speed of sound (created using R (4.4.1 – Package snha (Groth 2023)).

health. Furthermore, the research thoroughly examines the frequency of energy drink consumption and its subtle relationships with SOS, even at lower intake levels. The findings of this study confirm the original hypothesis, albeit the SNHA showed a non-direct association between energy drinks and SOS. Notably, those who consumed energy drinks 1–2 days per week and less than once a month showed a significant negative association with bone tissue quality, specifically those with a lower SOS, indicating potentially adverse effects on bone health. This finding is particularly interesting since it illustrates that even lower consumption frequencies are linked to a decreased SOS. This suggests that the ingredients contained in energy drinks might have more subtle than expected yet significant effects on bone metabolism, potentially influencing calcium absorption or altering hormonal balances crucial for bone health. Even at low doses, ranging from 1–4 days a month with the majority not exceeding one drink per day, a study by Malinauskas et al. (2007) observed side effects such as headaches and heart palpitations among 496 college students in the United States, highlighting the increasing concerns regarding potential health risks.

Comparable findings were also reported by Puupponen et al. (2023); the study encompassed a nationally representative sample of 2429 adolescents (1260 13-year-olds and 1169 15-year-olds) from 77 schools in Finland. The investigation revealed that frequent energy drink consumers exhibited a significantly higher likelihood of reporting several concerning behaviours compared to non-consumers, including elevated rates of smoking, snus use, cannabis use, alcohol consumption, problematic social media use, insufficient sleep, breakfast omission, inebriation, and inadequate dental hygiene. One of the primary components of these drinks is caffeine, which, as noted by Berman et al. (2022), may contribute to bone loss through various mechanisms, including non-specific inhibition of adenosine receptors involved in

Table 5 Observed percentages of individuals who either engage in medium intense physical activity or do not across different levels of energy drink consumption frequency

Energy drink consumption frequency	Physical activity (medium intensity) Yes	n	No	n	p	χ^2
Daily	0.3%	3	1.2%	11	0.507	5.292
5–6 days/week	0.2%	2	0.8%	7		
3–4 days/week	1.1%	10	1.2%	11		
1–2 days/week	2.5%	23	4.3%	39		
1–3 days/month	2.9%	26	6.4%	58		
<once a month	5.9%	54	13.0%	118		
None	17.8%	162	42.5%	387		

p statistical significance; n number of individuals, χ^2 chi-squared test

Table 6 Observed percentages of individuals who either engage in high-intensity physical activity or do not across different levels of energy drink consumption frequency

Energy drink consumption frequency	Physical activity (high-intensity) Yes	n	No	n	p	χ^2
Daily	0.2%	2	1.3%	12	0.420	6.027
5–6 days/week	0.1%	1	0.9%	8		
3–4 days/week	0.3%	3	2.0%	18		
1–2 days/week	1.3%	12	5.5%	50		
1–3 days/month	0.9%	8	8.3%	76		
<once a month	1.9%	17	17.0%	155		
None	5.9%	54	54.3%	495		

p statistical significance; n number of individuals, χ^2 chi-squared test

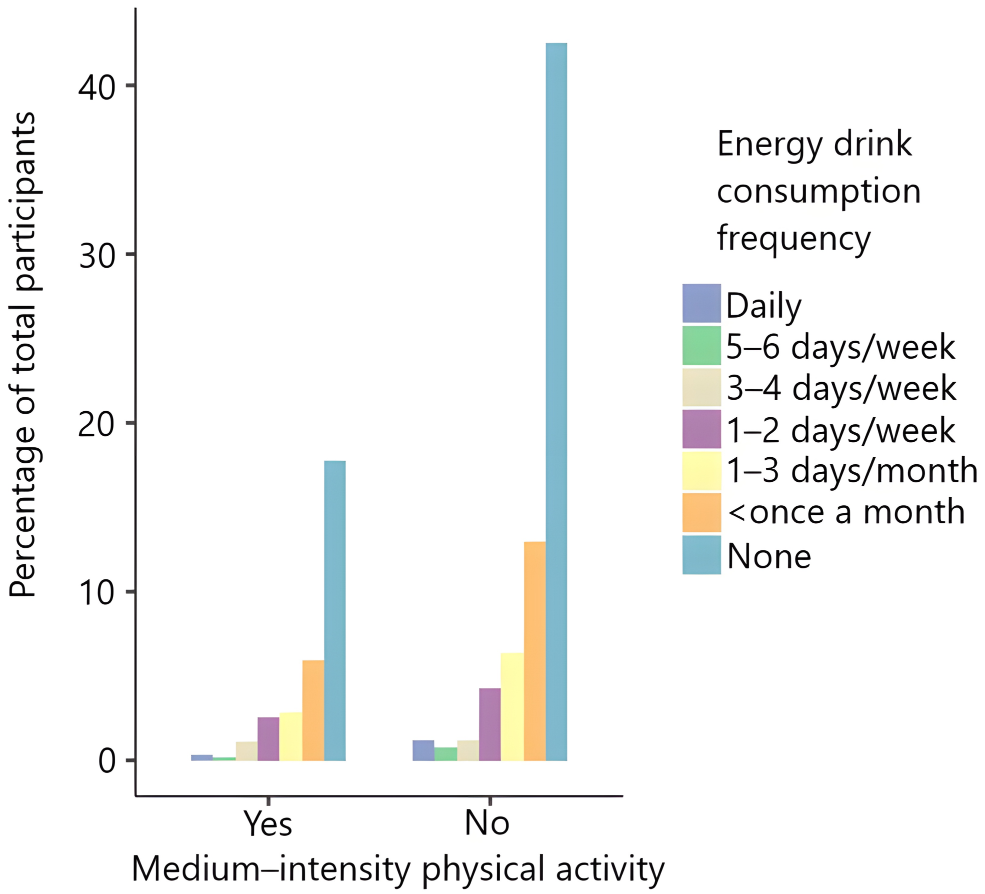

Figure 4 Bar plot illustration of the relationship between the energy drink consumption frequencyand engagement in medium-intensity physical activity of young Slovaks (created using jamovi version 2.3.21).

bone metabolism. Specifically, caffeine's competitive inhibition of adenosine A2 receptors could impede bone formation and promote bone resorption, while its effects on adenosine A1 receptors may have opposing effects. Additionally, caffeine may affect bone health by disrupting calcium metabolism and altering vitamin D responses (Berman et al. 2022). Similarly, Mubarak et al. (2023) found a significant association between cola consumption and the occurrence of low BMD, which may be related to the caffeine content in these drinks, although the sample of this study comprised only 85 women aged 40–70 years, thus older than the sample in the present study, indicating that age-related differences in bone metabolism could influence the observed results. Conversely, in our study, daily consumption and consumption at other frequencies did not show significant associations with SOS, which may be attributed to the small sample sizes of these categories or other unaccounted factors. In addition, in our sample, in contrast with the literature, no significant association was found between coffee consumption and SOS.

The absence of significant associations between BC (PBF and LBM) and mPhA suggests that other unmeasured variables, such as dietary patterns, genetic predispositions, or other lifestyle behaviours, may contribute to bone health in our study sample. Specifically, individuals who fail to engage in medium-intensity and high-intensity physical activity show contradicting energy drink consumption patterns.

Although the majority of these individuals avoid energy drinks entirely, they show a higher proportion of daily consumers compared to those who are physically active; therefore, it could be hypothesized that a dependence on energy drinks is present among individuals who are less active for various purposes, such as providing energy or other advantages (Byerley 2016). Similarly, Poulos and Pasch (2015) discovered that the consumption of energy drinks was connected to an increase in soda and frozen meal consumption, which may suggest an overall less healthy lifestyle associated with lower physical activity levels. On the other hand, those who practice physical activity, compared to those who do not practice it, tend to consume energy drinks less frequently and rely less on such beverages to sustain their activity levels. Larson et al. (2014) found that sports and energy drink consumption was associated with higher levels of moderate to vigorous physical activity and organized sports participation for both sexes, suggesting that adolescents who engage in physical activity may consume energy drinks to enhance their performance or restore energy; this trend was not observed in our study, potentially due to differences in population characteristics, activity levels, cultural differences, or variations in energy drink consumption, as it analyzed 2793 American adolescents aged 14.4 ± 2 years, while our participants were university students. Numerous other studies also observed ambiguous results, including research involving 439 college students who regularly consumed energy drinks. These participants either engaged in physical activity regularly or adopted unhealthy lifestyle habits such as alcohol consumption and smoking (Attila and Çakir 2011; Protano et al. 2023).

These results demonstrate the multifaced implications of consuming energy drinks on bone tissue, emphasizing the importance of further studies to investigate the complex relationships between lifestyle factors, nutrition, and bone mineral density. Moreover, the scarcity of comparable studies in the existing literature and conflicting results regarding caffeinated beverages highlight the need for more research on this subject. Furthermore, the differences between our findings and existing literature may also arise from methodological variations, such as the use of different techniques to assess bone quality. Moreover, our data on physical activity and energy drink consumption, similar to Larson et al. (2014), rely on self-reporting, which could introduce potential biases. These factors contribute to the observed discrepancies in results.

Study limitations

The primary limitation of this study was its cross-sectional design, which precluded any causal inferences. This research also lacked detailed information regarding the duration of energy drink consumption, the quantity consumed, and the specific type, rendering the ingredients and their quantities unknown. Moreover, the sample size, particularly among male participants, was limited. It is also important to acknowledge that the sample in this study consists mainly of university students, which may introduce a form of sampling bias. This group is relatively homogenous in terms of age and educational background compared to the broader population. As a result, the findings of this study may not be fully generalizable to the entire Slovak population. Additionally, it is important to acknowledge that due to the disproportionate sex distribution within the sample, findings related to sex as a predictor should be considered with caution. A further limitation of this research is that it lacks data on participants' nutrition patterns and their calcium and vitamin

D intake, which are essential for skeletal health. As a result, we cannot conclusively establish that the observed correlations between energy drink consumption and reduced SOS measurements are due to factors like decreased calcium absorption. As such, the findings should be interpreted with caution and seen as indicating a possible connection between energy drinks and bone quality, rather than definitive evidence of causation. Subsequent studies should include comprehensive evaluations of dietary habits, encompassing calcium and vitamin D supplements, to better understand how energy drinks may affect bone health. Furthermore, it is essential to perform a long-term study to obtain a more thorough insight into these interactions across time since evaluating bone mineral density at just one point in time fails to capture ongoing changes and the effects of these drinks on bone tissue.

Conclusion

In our study, no significant associations were observed between physical activity, BC, and SOS. While energy drinks were not found to directly affect bone tissue, certain consumption patterns showed significant correlations with decreased bone density. Specifically, consuming these beverages 1–2 days per week or less than once a month was associated with reduced bone mass. This finding suggests that even occasional intake may have detrimental effects on skeletal health. Given the increasing popularity of energy drinks among younger populations, it is crucial to address the potential risks linked to their consumption. Additional studies are necessary to thoroughly investigate this relationship and its implications.

Authors contribution:

Simona Sulis contributed to writing the manuscript, conceptualizing it, collecting data, and performing the statistical analysis. Lenka Vorobeľová and Darina Falbová designed the study, participated in data collection, reviewed, and edited the manuscript. Alexandra Hozáková participated in the data collection and writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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