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Association of dietary patterns of American adults with bone mineral density and fracture

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Abstract

Objective: In a representative sample of US adults, we investigated the associations of nutrient patterns (NP) with bone mineral density (BMD) and fractures.
Design: Cross-sectional.
Setting: US community-based National Health and Nutrition Examination Survey (NHANES).
Subjects: Participants with measured data on dietary intake and BMD from 2005 to 2010 were included. Principal components analysis was used to identify NP. BMD was measured using dual-energy X-ray absorptiometry. ANCOVA, adjusted logistic and linear regression models were employed, accounting for the complex survey design and sample weights.
Results: We included a total of 18 318 participants, with 47·0 % (*n* 8607) being men. The mean age was 45·8 years with no sex difference. Three NP emerged, explaining 55·9 % of the variance in nutrient consumption. Multivariable-adjusted linear regressions revealed significant inverse associations between the 'high-energy' NP (rich in carbohydrates and sugar, total fat and saturated fat) and total femur, femoral neck, trochanter and intertrochanter BMD (β coefficient: −0·029, −0·025, −0·034 and −0·021, respectively, all $P<0·001$), while there were significant associations between the 'nutrient-dense' NP (rich in vitamins, minerals and fibre) and 'healthy fat' NP (high dietary PUFA and MUFA) and BMD at total femur, femoral neck, trochanter and intertrochanter (all $P<0·001$). In adjusted logistic regression models, the odds of hip, wrist or spine fractures did not vary significantly across NP quartiles.
Conclusions: Nutrient-dense and healthy fat NP are associated with higher BMD at various bone sites, while the high-energy NP is inversely associated with BMD measures.

Keywords
Dietary patterns
Bone mineral density
Vitamins
Minerals

Osteoporosis is a systemic skeletal disease characterized by reduced bone mass and disrupted bone architecture, resulting in increased bone fragility and fracture risk[1]. Osteoporosis is commonly referred to as a 'silent disease' because it remains asymptomatic until a fracture occurs. Such osteoporotic fractures are a major cause of morbidity in the elderly population[2]. Low bone mineral density (BMD; i.e. number of standard deviations below the mean areal BMD for young adults, $T<-2·5$) is marker of osteoporosis and a predictor of low trauma fractures[3].

The accumulation and loss of bone mineral mass is influenced by various factors such as age, sex, ethnicity, heredity, lifestyle (physical activity and smoking) and nutritional status (Ca, protein and vitamin D intakes)[4]. Of these, diet is one of the most important modifiable determinants[5]. However, most studies have focused on a single nutrient or food/food group to examine the effects on bone health. These common approaches have methodological and conceptual limitations. They can detect the effects of single nutrients or foods on bone health but cannot explain the interactions among nutrients and food items[6]. We have comprehensively explained different approaches in evaluating the association between nutrient patterns (NP) and bone health elsewhere[7].

NP analysis has emerged as an alternative approach to overcome the aforementioned limitations in nutritional

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epidemiology[8]. In this approach, statistical methods are used to examine the pattern of intake of multiple foods or nutrients and derive single-exposure variables, or NP[9]. Such NP may provide an improved and more generalizable insight into diet–disease relationships[8]. Using the NP approach could facilitate the development of public health recommendations that are more convenient to follow[10]. Moreover, the human diet includes a range of different food items and complex mixtures of nutrients. Therefore, applying traditional methods (focusing on single nutrients) cannot take into consideration the numerous intercorrelations and interactions among foods and nutrients[8].

Although previous studies have examined the association of NP with BMD, the findings are conflicting. Some studies suggest an inverse relationship between an 'unhealthy' NP (characterized by red and processed meat, fats and sweets) and BMD, and a positive association between a 'healthy' NP (characterized by high consumption of fish, olive oil, fruits and vegetables, and low consumption of red meat and candy) and BMD[11–14]. Others have failed to show such associations[7,15]. For example, in a sample of 220 adult Greek women, adherence to a Mediterranean dietary pattern was not associated with indices of bone mass[7]. Another study of 1928 men and 4611 women from the Canadian Multicentre Osteoporosis Study found no consistent relationship between diet and BMD[15]. Given the inconsistencies across existing studies, we conducted the current study to identify NP associated with high or low BMD at different parts of the body (total femur, femoral neck, intertrochanter, trochanter, Ward's triangle, total spine, lumbar spine L1 to L4), as well as risk of fractures, in a nationally representative sample of US adults. We hypothesized that higher adherence to the Western diet would be associated with a less favourable index of bone health (BMD) and greater likelihood of fractures, while adherence to a healthy diet would be related with favourable bone health and lower risk of fractures.

Methods

Population

Data from the National Health and Nutrition Examination Surveys (NHANES) conducted between 2005 and 2010 were used for the present study. NHANES is a repeated cross-sectional survey conducted on an ongoing basis by the US National Center for Health Statistics, applying protocols and procedures described in detail previously[16]. All methods were performed in compliance with the Declaration of Helsinki on ethical standards for research involving human subjects[16]. NHANES uses a complex, multistage and stratified sampling design to select a sample representative of the civilian and non-institutionalized resident population of the USA. The National Center for Health Statistics Research Ethics Review Board approved the protocol and all participants provided informed consent[17]. Demographic information and interviews were collected using questionnaires administered during home visits, while trained personnel conducted a physical examination and biological sample collection in mobile examination units. The NHANES mobile examination centres are equipped with QDR 4500A fan-beam dual-energy X-ray absorptiometry densitometers (Hologic, Inc.) to measure BMD of the anterior–posterior lumbar spine and proximal femur. Details on measuring the BMD and protocols for the corresponding quality controls can be found elsewhere[18]. For fractures, we used data from self-reported hip, wrist (representing distal radius/ulna) and spine fractures[18]. A trained phlebotomist drew a blood specimen from the participant's antecubital vein. Detailed information on the measurement of C-reactive protein (CRP) concentrations are available elsewhere[19,20].

Dietary intake was assessed via 24 h recall by a trained interviewer, during the mobile examination centre visit, by use of a computer-assisted dietary interview system with standardized probes, i.e. the US Department of Agriculture Automated Multiple-Pass Method[21]. Briefly, the type and quantity of all foods and beverages consumed in a single 24 h period before the dietary interview (from midnight to midnight) were collected via the Automated Multiple-Pass Method, which is designed to enhance complete and accurate data collection while reducing the respondent burden[21].

For the present analysis, three survey cycles (i.e. 2005–2006, 2007–2008 and 2009–2010) were combined to produce estimates with greater precision and smaller sampling error. The analytical sample was limited to adults aged ≥18 years. After excluding pregnant and lactating (n 795) respondents, as well as those with missing information on the variables of interest (n 1325), the final analytical sample included 18 318 respondents from NHANES 2005–2010.

Statistical analysis

We analysed the data in compliance with prescribed guidelines for analysis of the complex NHANES data set, taking account of the masked variance and utilizing the proposed weighting methodology[22]. Factor analysis with orthogonal transformation (Varimax procedure) was applied to derive NP based on the nutrients. We used principal component factor analysis with Varimax orthogonal transformation to generate principal components representative of NP based on the highest correlation coefficients between the nutrients constituting each principal component[23]. All the necessary prerequisites of principal component analysis, including linearity, Kaiser–Meyer–Olkin measure of 0·88 and significant Bartlett's test of sphericity ($P<0·001$), were met. We then used regression methods to calculate the factor scores of each NP for each study participant[23]. Factors were retained for

further analysis based on their natural interpretation and eigenvalues on the scree test[24,25]. We computed the factor score for each NP by summing up intakes of nutrients weighted by their factor loadings (see online supplementary material, Supplemental Table 1). Each participant received a factor score for each identified pattern. Simple linear dose–response relationships are unlikely to be found in nutritional epidemiology[26]. To avoid issues with departure from a normal distribution and accordingly the distortion of regression coefficients by the extreme values, NP variables were categorized using population-specific quartiles of each NP before inclusion in regression models. The bottom or first quartile of each NP was then used as the reference category in all regression analyses. We computed means of BMD adjusted for age, sex, race/ethnicity, physical activity, smoking and CRP across the quartiles of each NP using ANCOVA. Categorical demographic variables were compared by using ANOVA and χ^2 tests, respectively. Fully adjusted multivariable linear regression models (adjusted for age, sex, race/ethnicity, physical activity, smoking and CRP) were used to determine the association of each NP score with BMD. Results were analysed using the complex sample module of the statistical software package IBM SPSS Statistics version 22.0. Sample weights were applied to account for unequal probabilities of selection, non-response bias and oversampling.

Results

The analytical sample comprised 18 318 participants, of whom 47·0 % (*n* 8607) were men. The mean age was 45·8 years in the overall sample and did not vary significantly between men and women ($P = 0{\cdot}126$). The White (non-Hispanic) population comprised the majority (69·4 %) of the participants. Furthermore, 56·1 % (*n* 8759) of the participants were married and 19·8 % were current smokers (23·9 % of the men and 16·7 % of the women). Overall, fewer participants engaged in a vigorous physical activity (5·2 %) than in little or no physical activity (24·0 %). As can be seen from Table 1, there were significant differences across quartiles of each NP with respect to race/ethnicity, education and sex distribution ($P < 0{\cdot}001$ for all comparisons). For each NP, participants in the upper higher quartile were younger than those in the bottom quartile ($P < 0{\cdot}001$ for all comparisons). Furthermore, participants in the upper quartile of the first NP had a higher level of CRP compared with those in the bottom quartile (0·45 *v.* 0·36 mg/dl, $P < 0{\cdot}001$), while participants in the upper quartile of the second and third NP had lower levels of CRP compared with those in the bottom quartile (both $P < 0{\cdot}001$; Table 1).

The principal component method uncovered three NP altogether explaining 55·9 % of the variance in consumption of dietary nutrients. The first NP was essentially representative of a diet high in carbohydrates and sugar, total fat

Table 1 Demographic characteristics of participants across quartiles of nutrient patterns (NP): US adults aged ≥18 years (*n* 18 318), National Health and Nutrition Examination Survey (NHANES) 2005–2010

	Quartile of 'high-energy' NP					Quartile of 'nutrient-dense' NP					Quartile of 'healthy fat' NP				
	Q1	Q2	Q3	Q4		Q1	Q2	Q3	Q4		Q1	Q2	Q3	Q4	
Characteristic	%	%	%	%	*P* value	%	%	%	%	*P* value	%	%	%	%	*P* value
Sex															
Male	31·1	41·1	51·4	71·1	<0·001	31·9	41·8	51·4	69·6	<0·001	30·7	41·6	51·1	71·1	<0·001
Female	68·9	58·9	48·6	28·9		68·1	58·2	48·6	30·4		69·3	58·4	48·9	28·9	
Race/ethnicity															
Mexican-American	20·5	19·6	19·0	17·3	<0·001	19·6	19·3	18·9	18·5	<0·001	17·4	18·4	19·3	21·1	<0·001
Other Hispanic	10·2	8·6	7·5	7·2		9·6	8·7	7·9	7·3		10·0	8·8	7·7	7·0	
White (non-Hispanic)	42·5	48·0	48·6	49·5		38·9	46·9	49·8	53·1		40·9	47·6	49·2	50·9	
Non-Hispanic Black	22·8	19·8	20·0	21·0		27·6	21·0	18·8	16·3		26·8	20·5	19·3	17·1	
Others	4·1	4·0	4·9	5·0		4·4	4·2	4·6	4·8		4·9	4·6	4·6	3·9	
Marital status															
Married	45·3	47·6	53·1	52·8	<0·001	44·5	51·2	55·1	54·5	<0·001	45·9	51·2	54·3	54·1	<0·001
Widowed	15·3	13·7	6·7	3·2		12·3	9·1	7·5	4·5		13·2	9·5	7·4	3·4	
Divorced	9·3	11·7	10·9	8·4		11·8	11·0	9·3	9·0		11·5	10·8	10·1	8·8	
Age (years)															
Mean	52·1	49·4	46·6	41·9	<0·001	49·2	49·0	47·7	43·6	<0·001	50·1	49·6	47·2	42·5	<0·001
SE	0·2	0·6	0·2	0·1		0·2	0·1	0·5	0·6		0·2	0·2	0·1	0·3	
C-reactive protein (mg/dl)															
Mean	0·36	0·37	0·42	0·45	<0·001	0·44	0·39	0·38	0·35	<0·001	0·43	0·41	0·38	0·37	<0·001
SE	0·01	0·02	0·01	0·01		0·03	0·02	0·01	0·01		0·01	0·01	0·02	0·01	
BMI (kg/m^2)	28·8	28·6	28·7	28·8	0·326	29·0	28·8	28·6	28·4	0·098	29·1	28·8	28·7	28·7	0·342
Fractures in hip	0·2	0·6	0·3	0·3	0·235	0·5	0·3	0·2	0·4	0·125	0·4	0·2	0·3	0·5	0·098
Fractures in wrist	1·6	3·2	2·9	1·2	0·101	2·1	3·0	1·6	2·2	0·082	2·9	1·6	2·3	2·1	0·123
Fractures in spine	0·6	0·7	0·6	0·4	0·253	0·5	0·8	0·5	0·5	0·182	0·6	0·5	0·6	0·6	0·428

Data are presented as percentages or as means with their standard errors where noted. ANOVA or the χ^2 test was applied.

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and saturated fat (called the 'high-energy' NP); the second NP was high in vitamins, minerals and fibre ('nutrient-dense' NP) and the third NP was mainly representative of high dietary PUFA and MUFA ('healthy fat' NP).

The age, sex, race/ethnicity, physical activity, smoking and CRP-adjusted means of BMD for different sites across quartiles of each NP are shown in Table 2. BMD at the total femur, femoral neck, trochanter and intertrochanter decreased significantly with increasing quartile of the high-energy NP ($P<0·001$ for all). BMD at the total femur, femoral neck and intertrochanter increased significantly across increasing quartiles of the nutrient-dense and healthy fat NP (all $P<0·001$). The profile of the associations was similar in age, sex, race/ethnicity, physical activity, smoking, CRP, BMI and hormone replacement therapy-adjusted linear regression models examining the continuous associations of NP with BMD. Indeed, there was a significant inverse association between the high-energy NP and total femur ($\beta=-0·029$), femoral neck ($\beta=-0·025$) and trochanter BMD ($\beta=-0·034$; all $P<0·001$). On the other hand, there was a significant positive association between the nutrient-dense and healthy fat NP and BMD at the total femur, femoral neck, trochanter and intertrochanter (all $P<0·001$; Table 2). No significant interactions were found between NP (all interaction $P>0·153$).

Percentage of fractures in the hip, wrist and spine were 1·4, 8·9 and 2·3 %, respectively. The rate of fracture by quartile of each NP is shown in Table 1. In logistic regression models adjusted for age, sex, race/ethnicity, physical activity, smoking, CRP, BMI and hormone replacement therapy, there was no significant variation across quartile of NP in the odds of fractures in the hip, wrist and spine (Table 3).

Discussion

Findings from the present study revealed that BMD at different sites of the proximal femur was inversely associated with a diet consisting highly of carbohydrates and sugar, total fat and saturated fat, and directly associated with a diet comprising vitamins, minerals and fibre. No association was found between NP and fractures, a finding to be interpreted in the context of a considerably low number of fractures.

In agreement with our results, several previous studies have demonstrated the direct association of fruits and vegetables (main sources of fibre, minerals and vitamins in the diet) with bone health[11,12,14,15]. The intake of fruits and vegetables in combination with fish was associated with high BMD in Japanese female farmers[12]. The existing Mediterranean diet score (MDS) was shown to be associated with high BMD[27]. Studies on the MDS and fracture risk have reported both unfavourable[28] and favourable[29] associations. The Mediterranean diet is

Table 2 Adjusted mean bone mineral density (BMD) across quartiles of nutrient patterns (NP) among US adults aged ≥18 years (*n* 18318), National Health and Nutrition Examination Survey (NHANES) 2005–2010

	Quartile of 'high-energy' NP (1)								Quartile of 'nutrient-dense' NP (2)								Quartile of 'healthy fat' NP (3)								NP score		
	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4		(1)	(2)	(3)
Variable	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	β	β	β
Total femur BMD (g/cm^2)	**0·99**	**0·001**	**0·98**	**0·001**	**0·97**	**0·001**	**0·96**	**0·001**	**0·96**	**0·001**	**0·97**	**0·002**	**0·98**	**0·001**	**0·99**	**0·002**	**0·96**	**0·003**	**0·97**	**0·002**	**0·98**	**0·002**	**0·99**	**0·002**	**−0·029**	**−0·029**	**0·036**
Femoral neck BMD (g/cm^2)	**0·86**	**0·004**	**0·85**	**0·002**	**0·84**	**0·003**	**0·83**	**0·001**	**0·83**	**0·001**	**0·84**	**0·004**	**0·85**	**0·002**	**0·86**	**0·002**	**0·83**	**0·006**	**0·84**	**0·004**	**0·85**	**0·004**	**0·86**	**0·003**	**−0·025**	**−0·025**	**0·031**
Trochanter BMD (g/cm^2)	**0·75**	**0·006**	**0·73**	**0·005**	**0·73**	**0·004**	**0·71**	**0·002**	0·72	0·003	0·73	0·006	0·73	0·003	0·74	0·004	0·72	0·008	0·73	0·006	0·74	0·008	0·74	**0·005**	**−0·034**	**−0·036**	**0·039**
Intertrochanter BMD (g/cm^2)	**1·17**	**0·004**	**1·16**	**0·003**	**1·15**	**0·005**	**1·13**	**0·003**	**1·14**	**0·004**	**1·15**	**0·008**	**1·16**	**0·002**	**1·17**	**0·006**	**1·13**	**0·004**	**1·15**	**0·003**	**1·16**	**0·008**	**1·17**	**0·007**	**−0·021**	**−0·022**	**0·028**
Ward's triangle BMD (g/cm^2)	0·71	0·009	0·70	0·007	0·70	0·001	0·69	0·002	0·69	0·005	0·70	0·005	0·71	0·002	0·71	0·003	0·69	0·002	0·70	0·003	0·71	0·005	0·71	0·003	−0·015	0·012	0·013
Total spine BMD (g/cm^2)	**1·05**	**0·004**	**1·04**	**0·006**	**1·03**	**0·005**	**1·01**	**0·002**	1·01	0·007	1·03	0·002	1·03	0·007	**1·04**	**0·006**	**1·01**	**0·006**	**1·02**	**0·003**	**1·03**	**0·003**	**1·04**	**0·002**	−0·019	**0·021**	0·014
L1 BMD (g/cm^2)	0·96	0·003	0·95	0·009	0·95	0·006	0·93	0·001	0·93	0·004	0·95	0·003	0·95	0·005	0·96	0·007	0·93	0·002	0·95	0·002	0·95	0·004	0·95	0·006	**−0·023**	0·016	−0·015
L2 BMD (g/cm^2)	1·04	0·002	1·04	0·003	1·03	0·007	1·02	0·004	1·02	0·003	1·04	0·001	1·04	0·006	1·04	0·002	1·01	0·009	1·04	0·007	1·04	0·007	1·04	0·008	0·012	−0·011	0·013
L3 BMD (g/cm^2)	1·06	0·009	1·06	0·002	1·06	0·009	1·04	0·006	1·04	0·002	1·06	0·006	1·06	0·003	1·06	0·001	1·04	0·005	1·06	0·004	1·06	0·008	1·06	0·004	−0·012	0·012	0·014
L4 BMD (g/cm^2)	1·07	0·001	1·06	0·007	1·06	0·004	1·04	0·004	1·04	0·001	1·06	0·008	1·06	0·002	**1·07**	**0·009**	**1·04**	**0·002**	**1·05**	**0·002**	**1·06**	**0·009**	**1·07**	**0·002**	0·011	−0·010	−0·013

Data are presented as means with their standard errors. ANCOVA was applied to calculate means adjusted for age, sex, race/ethnicity, physical activity, smoking, C-reactive protein, BMI and hormone replacement therapy. Adjusted linear regression was used to investigate the associations. Bold indicates significant differences across quartiles of a given NP.

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Table 3 Adjusted odds from logistic regression for the association of nutrient patterns (NP) with prevalent fractures among US adults aged ≥18 years (*n* 18 318), National Health and Nutrition Examination Survey (NHANES) 2005–2010

	Quartile of 'high-energy' NP								Quartile of 'nutrient-dense' NP								Quartile of 'healthy fat' NP							
	Q1	Q2		Q3		Q4			Q1	Q2		Q3		Q4			Q1	Q2		Q3		Q4		
Variable	Ref.	OR	95 % CI	OR	95 % CI	OR	95 % CI	*P* value	Ref.	OR	95 % CI	OR	95 % CI	OR	95 % CI	*P* value	Ref.	OR	95 % CI	OR	95 % CI	OR	95 % CI	*P* value
Fractures in hip	1·00	0·89	0·77, 1·12	1·06	0·62, 1·12	1·03	0·88, 1·11	0·235	1·00	0·74	0·56, 1·02	0·87	0·60, 1·29	0·63	0·56, 1·01	0·635	1·00	0·85	0·70, 1·09	0·89	0·73, 1·10	0·83	0·57, 1·01	0·125
Fractures in wrist	1·00	1·23	0·44, 1·62	0·88	0·69, 1·12	0·63	0·55, 1·02	0·415	1·00	0·63	0·50, 1·00	0·71	0·51, 1·11	0·96	0·99, 1·33	0·358	1·00	0·96	0·74, 1·22	0·79	0·56, 1·09	0·88	0·63, 1·10	0·436
Fractures in spine	1·00	1·02	0·92, 1·35	1·13	0·82, 1·39	0·76	0·61, 1·16	0·635	1·00	0·92	0·82, 1·23	0·63	0·56, 1·02	0·88	0·69, 1·10	0·426	1·00	0·80	0·60, 1·06	0·81	0·70, 1·26	0·65	0·43, 1·22	0·328

Ref., reference category.
Data are presented as odds ratios and 95 % confidence intervals. Models were adjusted for age, sex, race/ethnicity, physical activity, smoking, C-reactive protein, BMI and hormone replacement therapy.

known for its high content of cereals, legumes, fruits, nuts, vegetables, oils and fish, as well as low content of dairy and meat products. Although none of the patterns in our analyses of NHANES data exactly represents the Mediterranean diet, there are similarities with the nutrient-dense NP observed in our study, considering its high factor loadings for vitamins, minerals and fibre. Fruits and vegetables may act on bones by providing base buffers against excess dietary metabolic acids, increasing osteoclast activity that promotes bone resorption[30] and balancing the pH of body fluids to the physiological range[31]. In the Women's Health Initiative study, a low-fat and high-fruit, -vegetable and -grain diet intervention slightly decreased the risk of multiple falls and marginally lowered hip BMD in postmenopausal women[32]. However, Pedone *et al.* reported no relationship between dietary acid load and BMD in elderly women[33]. In a prospective study among 15 572 adults included in the China Health and Nutrition Survey, two dietary (traditional and modern) and two nutrient (plant- and animal-sourced) patterns were identified. During follow-up, participants in the upper tertile of the modern dietary and animal-sourced patterns had a 34 % (hazard ratio = 1·34; 95 % CI 1·06, 1·71) and 37 % (hazard ratio = 1·37; 95 % CI 1·08, 1·72) increase in fracture risk compared with those in the first tertile, respectively[34]. In another study evaluating the association between NP and BMD among elderly Australians, animal- and plant-sourced patterns were not associated with BMD, while a mixed-source pattern had protective effect on BMD loss[35].

After adjustment for CRP we found that there was still a significant relationship between BMD and NP, suggesting an independent role of diet on bone health. Studies have reported evidence on the role of inflammatory factors on bone remodelling. For example, in a study using NHANES III data (2807 females aged 65 years or older), there was an association between CRP and BMD[36]. Moreover, in another prospective study (1872 community-dwelling women), fracture risk increased with increasing CRP levels[37].

Diets rich in minerals and vitamins are positively associated with BMD[38]. The nutrient-dense pattern in our study represented minerals and vitamins that are beneficial for the fundamental architecture of bone[39,40]. The favourable effects of Ca and dairy food on bone health have been well established[39,40]. Minerals found in fruits and vegetables might contribute to healthy bone remodelling via a favourable impact on osteoblastic and osteoclastic activity. K and Mg may contribute to the acid–base balance in the body, as discussed before, and prevent bone loss. K could also increase the retention of Ca in the kidneys, independently of its role in the alkaline state of the body. Mg is also necessary for Ca metabolism. Vitamin C may affect bone health through its antioxidant properties, which suppress osteoclast activity[41]. It also acts as a cofactor for osteoblast differentiation and collagen

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formation[41]. Carotenoids and other antioxidants also affect bone health by reducing oxidative stress[41]. Vitamin K is involved in bone matrix formation, where mineralization happens[42].

We identified a pattern characterized by high consumption of carbohydrates, sugar, total fat and saturated fat, the high-energy NP, which is similar to ones identified in other studies[11,14,15]. McNaughton and co-workers[14] identified a 'high-energy nutrient-poor pattern' characterized by high intakes of refined cereals, soft drinks, fried potatoes, processed meat, beer, chocolate, confectionery and added sugar, and low consumption of vegetables, fruits and wholegrain cereals, which was significantly inversely associated with total body BMD. Similarly, for the 'candy pattern' observed by Tucker *et al.*[11] in the Framingham Cohort Study, a diet rich in refined foods and lacking in nutrient-dense foods may be detrimental to bone health in men. Indeed, participants in the 'candy' cluster had a lower BMD in comparison with individuals in the 'fruit, vegetables and cereal' and 'alcohol' clusters[11]. Furthermore, a recent study from Brazil found that a 'sweet foods, coffee and tea pattern' was inversely correlated with BMD[43]. Additionally, like the high-energy NP in our study, high intakes of fat and saturated fat showed a borderline inverse association with BMD among Japanese women[12].

Fish and seafood are rich in PUFA, especially *n*-3 fatty acids, which are known to have an anti-inflammatory impact that benefits bone[44]. We found the healthy fat NP to be associated with BMD in adults. A systematic review of ten randomized controlled trials revealed that *n*-3 and *n*-6 fatty acids when combined with Ca or dairy products had a significant impact on bone measures in some but not all trials[45]. The association between *n*-3 fatty acids and bone biomarkers and BMD could be explained by their anti-inflammatory effect, although more studies are needed to clarify the potential mechanisms.

There are several limitations to the present study. First, the results from our cross-sectional study, although nationally representative, cannot demonstrate a causal relationship. Second, although our analysis included known potential variables that can affect bone health in terms of environmental and genetic factors, residual confounding variables may still exist. We used a wide age range in adulthood that might not be the best approach in evaluating the association between NP and BMD. In an ideal situation, when sample size allows, women after menopause should be studied separately controlling for other potential covariates such as hormone replacement therapy. The statistical power was low to reliably investigate the association between NP and fracture. Moreover, fracture cases were assessed based on self-reports.

The study has several strengths. We had a sample selected randomly from the general US population. Therefore, the results obtained from this nationally representative sample can be extrapolated to the entire population. In addition, a large number of participants aged 18–80 years, the use of standardized procedures and the inclusion of both men and women are other important strengths.

A healthy nutrient-dense NP, characterized by high intakes of minerals, vitamins and fibre, may benefit BMD independent of potential confounding factors. In contrast, adherence to a high-energy NP characterized by high consumption of total and saturated fats, carbohydrates and sugar may pose a risk for low BMD.

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Supplementary material

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