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Association of visceral fat metabolic score with bone mineral density and osteoporosis: a NHANES cross-sectional study

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Abstract

Background Metabolic Score for Visceral Fat (METS-VF) is commonly used as an indicator for assessing visceral fat metabolism. However, the relationship between METS-VF, Bone Mineral Density (BMD), and osteoporosis remains unclear in the American population.

Methods This study utilized cross-sectional data from the National Health and Nutrition Examination Survey (NHANES), including participants aged 20 years and older, from the survey cycles conducted between 2005 and 2010, 2013–2014, and 2017–2018. Multivariable weighted linear regression and logistic regression analyses were first applied to investigate the associations between the METS-VF, femoral BMD, and osteoporosis. In addition, subgroup interaction analyses were performed to evaluate the robustness of these associations. To address potential non-linear relationships, restricted cubic spline regression was employed. All statistical analyses were conducted using R software version 4.3.3. P values were two-tailed, with $P < 0.05$ considered statistically significant.

Results After adjusting for all covariates, the positive correlations between METS-VF and BMD measurements at all sites remained statistically significant ($p < 0.001$ & p for trend < 0.001). Multivariable logistic regression analysis indicated that, after adjusting for covariates related to osteoporosis, each one-unit increase in METS-VF was associated with a 63.1% reduction in the risk of developing osteoporosis. Moreover, the direction of the associations between METS-VF and both BMD and osteoporosis remained consistent across all subgroups, while restricted cubic spline (RCS) analyses suggested nonlinear relationships. The 5.82–7.35 METS-VF range yielded a mean 51.9% osteoporosis risk reduction (sustained ≥ 30% peak efficacy in 66.7% of participants).

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Conclusions METS-VF demonstrated a nonlinear positive association with BMD and a nonlinear inverse relationship with osteoporosis risk. Future studies should establish optimal biological thresholds of METS-VF for skeletal health.

Clinical trial number Not applicable.

Keywords Visceral fat metabolism score, Bone mineral density, Osteoporosis, NHANES

Introduction

Bone Mineral Density (BMD) refers to the mineral content of bone tissue per unit area or volume, reflecting the strength and degree of mineralization of the bones. It is a crucial diagnostic indicator of osteoporosis [1]. Osteoporosis is a disease characterized by a reduction in bone mineral density and the destruction of bone structure. Its main features include a decrease in bone mass and the degradation of bone microstructure, which significantly increases the risk of fractures [2]. In recent years, osteoporosis has gradually become an important global health challenge, especially in the context of global population aging, placing tremendous pressure on the public health systems of various countries, such as regarding rising healthcare costs and increasing demand for care services [3]. Although high-risk groups for osteoporosis are primarily found in the elderly, particularly postmenopausal women, the incidence of osteoporosis in younger populations is rising annually due to changes in lifestyle [4]. Therefore, identifying factors related to BMD and osteoporosis is of significant importance.

Osteoporosis is a multifactorial disease, and its pathogenesis involves various factors such as obesity, hormones, lifestyle, nutrition, and chronic diseases [5]. Gender is a significant factor influencing BMD and osteoporosis, with substantial differences between men and women in bone metabolism, changes in bone mass, and the risk of osteoporosis [6]. Obesity has both positive and negative effects on osteoporosis. Research indicates that body mass index (BMI) has a threshold effect on BMD [7], and waist circumference, an important indicator for assessing visceral fat accumulation, is significantly associated with osteoporosis [8]. Moderate amounts of body fat may help protect the bones [9]. Insulin resistance is also closely linked to disturbances in bone metabolism [10]. Studies show that insulin resistance is associated with a decline in BMD, particularly in women and the elderly. Insulin resistance may affect bone metabolism regulatory factors, such as insulin-like growth factor (IGF), which in turn influences osteoporosis [11]. Insulin resistance shares common underlying factors with elevated fasting blood glucose and high triglycerides. Research has shown that elevated fasting blood glucose is associated with increased BMD [12], while elderly patients with higher serum cholesterol and triglyceride levels generally have lower BMD and higher risk of osteoporosis [13].

The Metabolic Score for Visceral Fat (METS-VF) is a scoring system that combines metabolic syndrome and visceral fat levels. It is calculated based on fasting blood glucose, triglycerides, high-density lipoprotein cholesterol, waist circumference, BMI, gender, and age, with the aim of assessing an individual's metabolic health and visceral fat status [14]. Unlike traditional adiposity markers, such as MRI and the BMI, the METS-VF incorporates factors like the metabolic score for insulin resistance index (METS-IR), and the waist-to-height ratio (WHtR), making it more effective at reflecting visceral fat distribution and predicting associated risks. Compared with BMI and waist circumference (WC), METS-VF is easier to measure visceral adipose area (VFA) [15].

The proximal femur (especially the femoral neck and intertrochanteric region) is the most active area for bone remodeling among the bodys weight-bearing bones, showing heightened sensitivity to metabolic changes (such as inflammatory factors derived from visceral fat), which can more promptly reflect the erosive effects of metabolic abnormalities on bone quality [16]. DXA is the most widely used technique for measuring bone density. When measured in the hip rather than the spine or forearm, DXA is more predictive of hip fractures [17].

The METS-VF score has been reported to efficiently assess diseases such as cardiovascular conditions and kidney stones [18, 19], In orthopedic diseases, METS-VF can be used as a more accurate indicator for the diagnosis of osteoarthritis [20]. However, the relationship between METS-VF, BMD, and osteoporosis has yet to be explored. To investigate the relationship between METS-VF and BMD and osteoporosis, we hypothesize that METS-VF is positively associated with BMD and negatively associated with osteoporosis, potentially through metabolic mechanisms, This study uses cross-sectional data from the National Health and Nutrition Examination Survey (NHANES).

Materials and methods

Data sources and study population

NHANES is a deinstitutionalized two-year survey of samples of the U.S. population held by the Centers for Disease Control and Prevention (CDC), hoping to assess the health and dietary status of the U.S. population. It incorporates multiple face-to-face interviews, physical examinations, questionnaires, and laboratory tests, and data are obtained through a multistage probability

sampling design. NHANES employs inverse probability weighting and post-stratification adjustments to ensure that sample-derived inferences are representative of the non-institutionalized U.S. population. Ignoring these weights may introduce bias and compromise the generalizability of findings.

Participants are provided with the institutional informed consent prior to both the interview and examination phases. All procedures are standardized by the NCHS Research Ethics Review Board according to the U.S. Department of Health and Human Services (HHS) Policy for the Protection of Human Research Subjects. For a detailed description of the NHANES survey methodology and data sources, please access the website (http://www.cdc.gov/nchs/nhanes/index.htm).

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Based on relevant questionnaires and laboratory test results, this study used data from five separate NHANES survey cycles (2005–2010, 2013–2014, 2017–2018) for a cross-sectional analysis. Participants from the 2011–2012 and 2015–2016 cycles were excluded due to missing data on femoral osteoporosis or bone mineral density measurements. A total of 50,463 individuals participated in the survey, and inclusion and exclusion criteria were applied as follows: (1) age ≥ 20 years; (2) complete bone mineral density (BMD) data; (3) complete data required for METS-VF score calculation; (4) participants without cancer or renal failure; (5) participants with missing data on other conditions (heart failure, stroke, liver disease). We first excluded 1,117 patients with cancer and renal failure (895 with cancer, 262 with renal failure, no missing values); for heart failure (17 cases), stroke (7 cases), and liver disease (17 cases), we uniformly excluded those with missing data, totaling 40 patients. Ultimately, 7,385 participants were included in this study for analysis(Fig. 1).

Assessment of osteoarthritis

Dual-energy X-ray absorptiometry (DXA) was used to measure BMD at different femoral regions, scans with Hologic QDR-4500 A fan-beam densitometers (Hologic, Inc., Bedford, MA, United States). According to the classification criteria (WHO 1994) established by the World Health Organization, BMD values in any femur region can be defined as osteoporosis if they fall below −2.5 standard deviations from the reference group for young adults [21]. The femoral regions that were evaluated in the study included the total femur, femoral neck, trochanter, and intertrochanter. The corresponding thresholds for osteoporosis were 0.68 g/cm^2, 0.59 g/cm^2, 0.49 g/cm^2, and 0.78 g/cm^2, respectively [22].

Assessment of visceral fat metabolic score

The METS-VF is an index that can be adopted for assessing the visceral fat accumulation and associated metabolic health of an individual. In this study, METS-VF was calculated using the following formula: METS-VF = 4.466 + 0.011[(Ln (METS-IR))^3] + 3.239[(Ln (WHtR))^3] + 0.319(Sex) + 0.594(Ln (Age)) ("male" = 1, "female" = 0). The metabolic insulin resistance score (METS-IR) was calculated with the formula: METS-IR = Ln [(2 × fasting glucose) + fasting triglycerides) × BMI] / [Ln (high-density lipoprotein cholesterol)]. In addition, waist-to-height ratio (WHtR) was calculated by WHtR = WC / HT.

Covariates

Continuous covariates included age, total calcium, uric acid, creatinine, Healthy Eating Index-2020 (HEI-2020), and depression score. The USDA and NCI established the HEI-2020 as a metric to evaluate diet quality in accordance with the Dietary Guidelines for Americans [23]. This study utilized 28 parameters from the NHANES data to compute this index using the dietaryindex R package [24]. The depression score was calculated using the self-reported PHQ-9 scale.

Race/ethnicity (non-Hispanic White, Mexican American, non-Hispanic Black, other Hispanic, or other race/multiracial), education level (less than high school/high school graduate/college graduate), marital status (married/cohabiting or unmarried/widowed/divorced/separated), poverty-to-income ratio (poor/not poor), alcohol use (yes/no), smoking status (never smoked/former smoker/current smoker), physical activity (inactive/moderate/intense exercise/both moderate and intense exercise), heart failure (yes/no), stroke (yes/no), hypertension (yes/no), and diabetes (yes/no) were used as categorical variables.

Alcohol use was determined from two 24-hour dietary recall surveys; if participants reported alcohol consumption in at least one of the surveys, they were classified as alcohol users. Smoking status was assessed as never smoked (smoked < 100 cigarettes), former smoker (currently not smoking but smoked ≥ 100 cigarettes), or current smoker (≥ 100 cigarettes, currently smoking every day or some days). Physical activity was evaluated based on the participant-reported engagement in vigorous physical activity (high-intensity activities such as running or basketball) and moderate physical activity (such as brisk walking, swimming, or regular cycling). Missing data were imputed using the missForest R package, a random forest-based technique that is highly computationally efficient for high-dimensional data with both categorical and continuous predictors [25]. Missing values

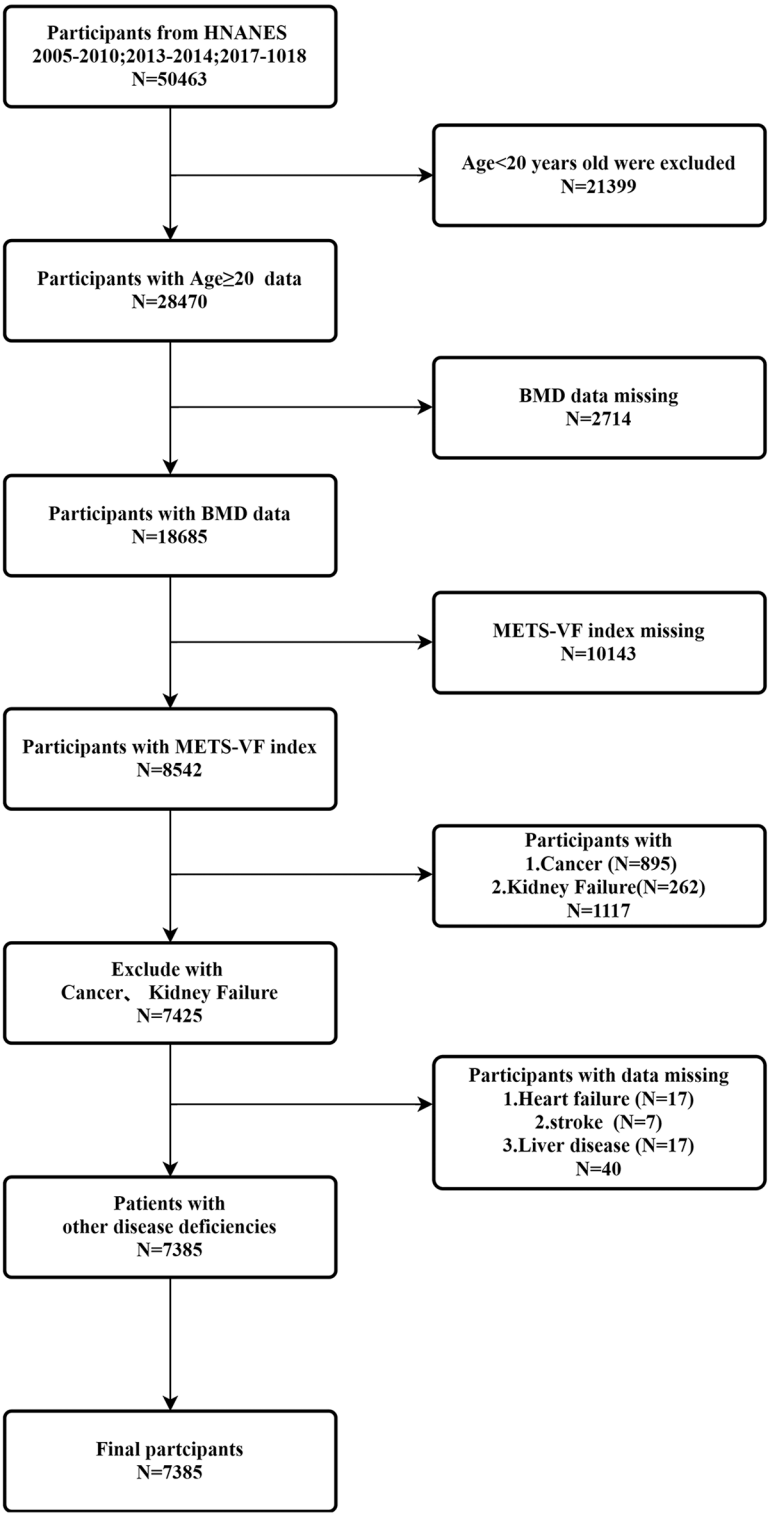

Fig. 1 The flowchart of participant selection

are iteratively imputed by predicting each variable's missing data using random forest models trained on other variables, cycling until convergence.

Daniel J artificially set missing value proportions of 10%,20%, and 30% in their study to compare the effectiveness of multiple imputation methods, with MissForest always providing better imputation. On the other hand, the number of missing values seems to have little impact on the performance of all methods (missing ratio of 10-30%). This study did not encounter variable missing values exceeding 15% (Supplementary Table 1).

Statistical analysis

We represent categorical variables as percentages, while we denote continuous variables as medians accompanied by interquartile ranges [IQR]. The χ^2 test was used to compare categorical variables between groups. For continuous variables, Krus-kal-Wallis H test was used to compare variables between groups. The Metabolic Score for Visceral Fat was categorized into four groups based on quartiles: Q1, Q2, Q3, and Q4. We employed weighted generalized linear regression to investigate the association between METS-VF, both as a continuous and a categorical variable, and bone density and osteoporosis. Next, three models were constructed based on different covariates, and a trend analysis was conducted for each model. Furthermore, subgroup analyses stratified by age, sex, race, marital, educational level, ratio of family income to poverty, smoking, heart failure, stroke, hypertension, and diabetes were also conducted. Finally, weighted restricted cubic splines (RCS) with four knots were employed to assess the nonlinear association between METS-VF and bone density and osteoporosis in the third model. All statistical analyses were conducted using R software version 4.3.3. *P* values were two-tailed, with $P < 0.05$ considered statistically significant.

Results

Participant characteristics

The characteristics of the study population categorized by METS-VF index quartiles are presented in Table 1. A total of 7,385 participants were included in the analysis. Overall, significant differences were observed in the characteristics of the study variables, except for PIR (ratio of family income to poverty), depression score, HEI (Healthy Eating Index), and Femoral Neck BMD ($p < 0.05$). Regarding categorical variables, as the METS-VF index increased, the percentages of participants who were male, married, engaged in inactive physical activities, and those with heart failure, stroke, hypertension, and diabetes also increased. Conversely, the percentages of participants with a college degree or higher, currently smoking or drinking, and those diagnosed with osteoporosis decreased. For continuous variables, participants in higher METS-VF index groups exhibited greater values for age, uric acid, creatinine, Total Femur BMD, Trochanter BMD, and Intertrochanter BMD.

Multivariable regression analysis

In our analysis focusing on BMD as the dependent variable, we constructed 36 weighted generalized linear regression models using METS-VF as a continuous variable, a categorical variable classified into quartiles, and a continuous variable transformed from quartiles as independent variables. These models were categorized into three groups based on the number of covariates included: Model 1, Model 2, and Model 3. As presented in Table 2, METS-VF demonstrated a positive correlation with Total Femur BMD, Trochanter BMD, and Intertrochanter BMD relative to the reference level (Q1). Notably, after adjusting for all covariates, the positive association between METS-VF and all BMD measures remained statistically significant ($p < 0.001$ & p for trend < 0.001). For each one-unit increase in METS-VF, the Total Femur BMD increased by 0.077 g/ cm^2 (95% CI: 0.071–0.084, $p < 0.001$); the Femoral Neck BMD increased by 0.059 g/ cm^2 (95% CI: 0.052–0.066, $p < 0.001$); the Trochanter BMD increased by 0.055 g/ cm^2 (95% CI: 0.049–0.060, $p < 0.001$); and the Intertrochanter BMD increased by 0.091 g/ cm^2 (95% CI: 0.083–0.099, $p < 0.001$). When osteoporosis was considered as the dependent variable, the results from the weighted multivariable logistic regression model indicated that, after adjusting for covariates associated with osteoporosis, higher METS-VF scores (Q4 and Q3) were associated with a reduced risk of osteoporosis, with respective reductions of 72.5% and 83.8%. The trend analysis showed a statistically significant effect (p for trend < 0.001). Furthermore, for each one-unit increase in METS-VF, the risk of developing osteoporosis decreased by approximately 63.1%.

Subgroup analyses

As shown in the figure, the positive association between METS-VF and BMD remained significant. However, the strength of this association varied across certain subgroups, as indicated by significant interaction effects (p for interaction < 0.05). For total femur BMD, the association between METS-VF and BMD differed significantly by age, sex, marital status, smoking status, heart failure, hypertension, and diabetes (Fig. 2A). For femoral neck BMD, the association varied by age, marital status, heart failure, hypertension, and diabetes (Fig. 2B). For trochanter BMD, the association was modified by age, marital status, PIR, hypertension, and diabetes (Fig. 2C). For intertrochanter BMD, the association showed differences depending on age, sex, marital status, smoking status, heart failure, hypertension, and diabetes (Fig. 2D). We observed that the positive associations between

Table 1 Clinical characteristics by METS-VF quartiles (p-values for interquartile differences)

Variables	Metabolic Score for Visceral Fat					*p*-value
	Overall(*n* = 7385)	Q1(*n* = 1561)	Q2(*n* = 1757)	Q3(*n* = 1992)	Q4(*n* = 2075)	
Age, years	48.81 ± 15.66	37.85 ± 13.78	46.40 ± 14.52	52.00 ± 13.87	59.01 ± 12.12	**< 0.001**
Sex, (%)						
Male	50.81	37.62	47.01	51.96	66.66	**< 0.001**
Female	49.19	62.38	52.99	48.04	33.34	
Race, (%)						
Mexican American	8.48	6.52	8.64	11.11	7.65	**< 0.001**
Other Hispanic	5.25	3.70	6.00	5.94	5.35	
Non-Hispanic White	68.69	69.80	67.04	64.55	73.35	
Non-Hispanic Black	10.48	10.79	10.72	11.36	9.03	
Other Race	7.11	9.18	7.60	7.04	4.61	
Marital status, (%)						
No	33.60	40.51	32.60	30.64	30.66	**< 0.001**
Yes	66.40	59.49	67.40	69.36	69.34	
Educational level, (%)						
Under High school	6.05	3.80	5.08	7.69	7.62	**< 0.001**
Completed high school	11.41	10.15	10.17	12.54	12.79	
College degree or above	82.54	86.05	84.74	79.77	79.59	
PIR	3.08 ± 1.58	3.14 ± 1.60	3.10 ± 1.58	3.03 ± 1.59	3.05 ± 1.57	0.482
Physical activity, (%)						
Inactive	42.50	39.02	42.79	42.97	45.23	**< 0.001**
Moderate	28.93	27.13	26.34	30.54	31.72	
Vigorous	5.56	5.42	5.32	5.59	5.89	
Both moderate and vigorous	23.01	28.43	25.56	20.91	17.16	
Smoking status, (%)						
Never	53.23	55.67	54.92	54.76	47.55	**< 0.001**
Former	25.54	16.13	21.81	26.44	37.79	
Current	21.23	28.20	23.27	18.81	14.66	
Alcohol use, (%)						
No	85.97	83.01	84.44	86.85	89.57	**< 0.001**
Yes	14.03	16.99	15.56	13.15	10.43	
Depression	2.63 ± 3.76	2.44 ± 3.46	2.52 ± 3.54	2.75 ± 3.96	2.83 ± 4.03	**0.017**
Heart failure, (%)						
No	98.23	99.68	99.11	98.36	95.78	**< 0.001**
Yes	1.77	0.32	0.89	1.64	4.22	
Stroke, (%)						
No	97.68	99.45	98.62	97.32	95.35	**< 0.001**
Yes	2.32	0.55	1.38	2.68	4.65	
Hypertension, (%)						
No	63.34	85.46	72.77	58.10	37.00	**< 0.001**
Yes	36.66	14.54	27.23	41.90	63.00	
Diabetes, (%)						
No	87.41	98.24	94.70	85.63	71.04	**< 0.001**
Yes	12.59	1.76	5.30	14.37	28.96	
HEI-2020	51.40 ± 11.20	51.94 ± 11.42	51.66 ± 11.25	51.63 ± 11.14	50.38 ± 10.93	0.068
Total calcium, mg/dL	9.39 ± 0.34	9.43 ± 0.33	9.41 ± 0.33	9.38 ± 0.34	9.35 ± 0.36	**< 0.001**
Uric acid, mg/dL	5.48 ± 1.37	4.75 ± 1.16	5.25 ± 1.23	5.72 ± 1.31	6.20 ± 1.35	**< 0.001**
Creatinine, mg/dL	0.88 ± 0.20	0.83 ± 0.16	0.86 ± 0.19	0.88 ± 0.21	0.94 ± 0.24	**< 0.001**
Total femur BMD, g/cm^2	0.97 ± 0.16	0.94 ± 0.15	0.95 ± 0.15	0.98 ± 0.16	1.01 ± 0.15	**< 0.001**
Femoral neck BMD, g/cm^2	0.83 ± 0.15	0.82 ± 0.14	0.82 ± 0.15	0.83 ± 0.15	0.84 ± 0.15	0.064
Trochanter BMD, g/cm^2	0.73 ± 0.13	0.71 ± 0.12	0.72 ± 0.13	0.74 ± 0.13	0.77 ± 0.13	**< 0.001**
Intertrochanter BMD, g/cm^2	1.15 ± 0.18	1.10 ± 0.17	1.13 ± 0.18	1.16 ± 0.18	1.20 ± 0.18	**< 0.001**
Osteoporosis, (%)						

Table 1 (continued)

Variables	Metabolic Score for Visceral Fat					*p*-value
	Overall(*n* = 7385)	Q1(*n* = 1561)	Q2(*n* = 1757)	Q3(*n* = 1992)	Q4(*n* = 2075)	
No	94.60	94.80	92.89	94.84	95.85	**0.015**
Yes	5.40	5.20	7.11	5.16	4.15	
VAI	4.66 ± 7.89	2.53 ± 3.31	3.86 ± 3.65	5.31 ± 5.66	6.92 ± 13.49	**< 0.001**
METS-VF	6.77 ± 0.71	5.77 ± 0.49	6.67 ± 0.15	7.10 ± 0.11	7.54 ± 0.18	**< 0.001**

Number (n) matches the actual number of cases sampled, and all other analyses are weighted. Data were Mean ± SD for continuous variables or proportions for categorical variables

Abbreviations: PIR, ratio of family income to poverty; HEI, healthy eating index; BMD, bone mineral density; VAI, visceral adiposity index

Table 2 Association between metabolic score for visceral fat and femur BMD (Osteoporosis) in the multiple regression model

Variables	Model 1			Model 2			Model 3		
	β/OR	95%CI	*p*-value	β/OR	95%CI	*p*-value	β/OR	95%CI	*p*-value
Total femur BMD, g/cm²									
METS-VF	0.040	0.034–0.046	**< 0.001**	0.084	0.078–0.090	**< 0.001**	0.077	0.071–0.084	**< 0.001**
(Intercept)	0.938	0.929–0.947	**< 0.001**	1.164	1.151–1.177	**< 0.001**	1.265	1.163–1.367	**< 0.001**
[Q2]	0.017	0.004–0.030	**0.012**	0.048	0.038–0.059	**< 0.001**	0.045	0.035–0.055	**< 0.001**
[Q3]	0.041	0.028–0.054	**< 0.001**	0.094	0.083–0.105	**< 0.001**	0.085	0.074–0.097	**< 0.001**
[Q4]	0.076	0.064–0.088	**< 0.001**	0.150	0.138–0.162	**< 0.001**	0.137	0.124–0.150	**< 0.001**
P for trend	**< 0.001**			**< 0.001**			**< 0.001**		
Femoral neck BMD, g/cm²									
METS-VF	0.006	0.000–0.012	**0.039**	0.065	0.059–0.071	**< 0.001**	0.059	0.052–0.066	**< 0.001**
(Intercept)	0.824	0.815–0.834	**< 0.001**	1.056	1.044–1.068	**< 0.001**	1.142	1.034–1.250	**< 0.001**
[Q2]	-0.004	-0.018–0.011	0.596	0.039	0.027–0.051	**< 0.001**	0.035	0.023–0.047	**< 0.001**
[Q3]	0.003	-0.010–0.016	0.636	0.074	0.063–0.085	**< 0.001**	0.065	0.053–0.077	**< 0.001**
[Q4]	0.012	0.001–0.024	**0.034**	0.116	0.105–0.128	**< 0.001**	0.103	0.090–0.116	**< 0.001**
P for trend	**0.017**			**< 0.001**			**< 0.001**		
Trochanter BMD, g/cm²									
METS-VF	0.032	0.026–0.037	**< 0.001**	0.060	0.054–0.066	**< 0.001**	0.055	0.049–0.060	**< 0.001**
(Intercept)	0.707	0.700–0.714	**< 0.001**	0.856	0.844–0.868	**< 0.001**	0.951	0.862–1.039	**< 0.001**
[Q2]	0.012	0.001–0.023	**0.031**	0.033	0.024–0.042	**< 0.001**	0.030	0.021–0.039	**< 0.001**
[Q3]	0.033	0.022–0.044	**< 0.001**	0.068	0.058–0.078	**< 0.001**	0.061	0.051–0.071	**< 0.001**
[Q4]	0.062	0.051–0.072	**< 0.001**	0.109	0.097–0.120	**< 0.001**	0.098	0.087–0.109	**< 0.001**
P for trend	**< 0.001**			**< 0.001**			**< 0.001**		
Intertrochanter BMD, g/cm²									
METS-VF	0.051	0.044–0.058	**< 0.001**	0.099	0.092–0.106	**< 0.001**	0.091	0.083–0.099	**< 0.001**
(Intercept)	1.104	1.094–1.115	**< 0.001**	1.360	1.345–1.376	**< 0.001**	1.473	1.347–1.599	**< 0.001**
[Q2]	0.024	0.009–0.039	**0.002**	0.058	0.046–0.070	**< 0.001**	0.054	0.042–0.066	**< 0.001**
[Q3]	0.054	0.039–0.069	**< 0.001**	0.111	0.097–0.125	**< 0.001**	0.100	0.086–0.115	**< 0.001**
[Q4]	0.098	0.083–0.112	**< 0.001**	0.177	0.162–0.192	**< 0.001**	0.160	0.144–0.177	**< 0.001**
P for trend	**< 0.001**			**< 0.001**			**< 0.001**		
Osteoporosis									
METS-VF	0.959	0.826–1.113	0.576	0.354	0.282–0.443	**< 0.001**	0.369	0.281–0.485	**< 0.001**
(Intercept)	0.055	0.042–0.072	**< 0.001**	0.000	0.000–0.000	**< 0.001**	0.012	0.000–0.969	**0.048**
[Q2]	1.395	0.952–2.043	0.087	0.644	0.407–1.019	0.060	0.638	0.394–1.035	0.068
[Q3]	0.991	0.688–1.427	0.961	0.272	0.174–0.424	**< 0.001**	0.275	0.173–0.438	**< 0.001**
[Q4]	0.788	0.541–1.148	0.212	0.162	0.104–0.251	**< 0.001**	0.162	0.100–0.261	**< 0.001**
P for trend	0.053			**< 0.001**			**< 0.001**		

MEC weight was adjusted; For BMD, the effect size is *β*; for osteoporosis, the effect size is OR

Model 1: no covariates were adjusted; Model 2: age, gender, and race were adjusted; Model 3: age, gender, race, marital status, education level, physical activity, PIR, smoking status, total calcium, uric acid, creatinine, heart failure, stroke, hypertension, diabetes, HEI-2020, depression

Abbreviations: METS-VF, metabolic score for visceral fat; BMD, bone mineral density; PIR, poverty and income ratio; HEI-2020, Healthy Eating Index-2020; β, regression coefficient; OR, odds ratio; MEC Mobile Examination Center

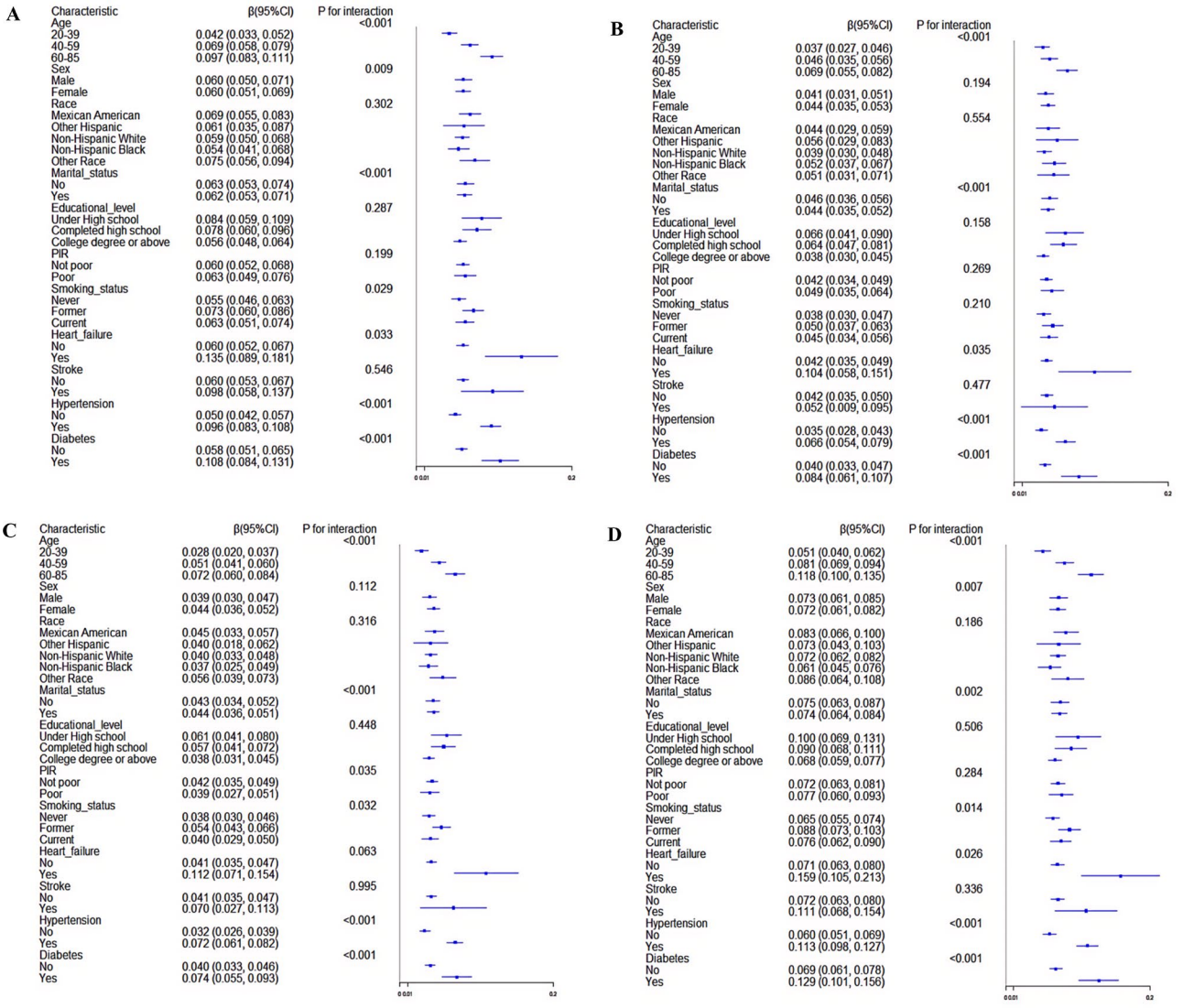

Fig. 2 **A** Subgroup analysis of the association between METS-VF and total femoral BMD. **B** Subgroup analysis of the association between METS-VF and femoral neck BMD. **C** Subgroup analysis of the association between METS-VF and trochanteric BMD. **D** Subgroup analysis of the association between METS-VF and intertrochanteric BMD

METS-VF and BMD at all four skeletal sites were consistently weaker in younger participants, non-hypertensive individuals, and those without diabetes (all p for interaction < 0.001).

To further assess the robustness of the association between METS-VF, BMD, and osteoporosis, subgroup interaction analyses were performed for age (20–39, 40–59, 60–85), sex, race, marital status, educational level, PIR, smoking status, heart failure, stroke, hypertension, and diabetes. In these analyses, METS-VF was treated as a continuous variable, and other covariates in Model 3 were included.

As shown in the figure, the positive association between METS-VF and BMD remained significant. However, the strength of this association varied across certain subgroups, as indicated by significant interaction effects (p for interaction < 0.05). For total femur BMD, the association between METS-VF and BMD differed significantly by age, sex, marital status, smoking status, heart failure, hypertension, and diabetes (Fig. 2A). For femoral neck BMD, the association varied by age, marital status, heart failure, hypertension, and diabetes (Fig. 2B). For trochanter BMD, the association was modified by age, marital status, PIR, hypertension, and diabetes (Fig. 2C). For intertrochanter BMD, the association showed differences depending on age, sex, marital status, smoking status, heart failure, hypertension, and diabetes (Fig. 2D). We observed that the positive associations between METS-VF and BMD at all four skeletal sites were consistently weaker in younger participants,

non-hypertensive individuals, and those without diabetes (all p for interaction < 0.001).

Overall, the positive association between METS-VF and BMD was more pronounced in participants who were older, unmarried, and had hypertension or diabetes. Notably, the negative correlation between METS-VF and osteoporosis remained stable across all subgroups, with significant interactions observed with age and hypertension ($p < 0.01$). The most significant demographic characteristics included participants aged 20–39 years (OR = 0.153, 95% CI: 0.104–0.223) or 60–85 years (OR = 0.373, 95% CI: 0.261–0.532), and those with hypertension (OR = 0.288, 95% CI: 0.201 – 0.414) (Fig. 3).

Non-linear association

To clarify whether there is a nonlinear relationship between METS-VF, BMD, and osteoporosis, a weighted RCS analysis was conducted, with all previously mentioned covariates included. The results indicated that METS-VF exhibited a nonlinear relationship with BMD at various sites (p for nonlinear < 0.01) (Fig. 4), and also a nonlinear relationship with osteoporosis (p for nonlinear < 0.001) (Fig. 5).

As shown in Fig. 6, the 5.82–7.35 METS-VF range was associated with a mean 51.9% reduction in osteoporosis risk (risk reduction rate ≥ 30% of peak value), encompassing 66.7% of participants.

Discussion

In this large cross-sectional study based on the U.S. population, utilizing data from the 2005–2010, 2013–2014, and 2017–2018 NHANES surveys, we systematically evaluated, for the first time, the relationship between METS-VF and BMD as well as the risk of osteoporosis. We further revealed the nonlinear relationship between METS-VF and femoral BMD. Specifically, METS-VF was significantly positively associated with total femur BMD, femoral neck BMD, trochanter BMD, and intertrochanter BMD, with each unit increase in METS-VF corresponding to approximately a 63.1% reduction in the risk of osteoporosis, in the 5.82–7.35 METs-VF range, a mean 51.9% reduction in osteoporosis risk was demonstrated (risk reduction rate ≥ 30% of peak value), covering 66.7% of study participants.These findings highlight the complex role of METS-VF in bone health, suggesting that its impact on BMD and osteoporosis is not merely linear but is regulated by multiple factors.

Previous studies have focused on the relationship between single indicators such as BMI or visceral fat volume and BMD or osteoporosis risk, yielding inconsistent results [26, 27]. BMI is calculated solely based on weight

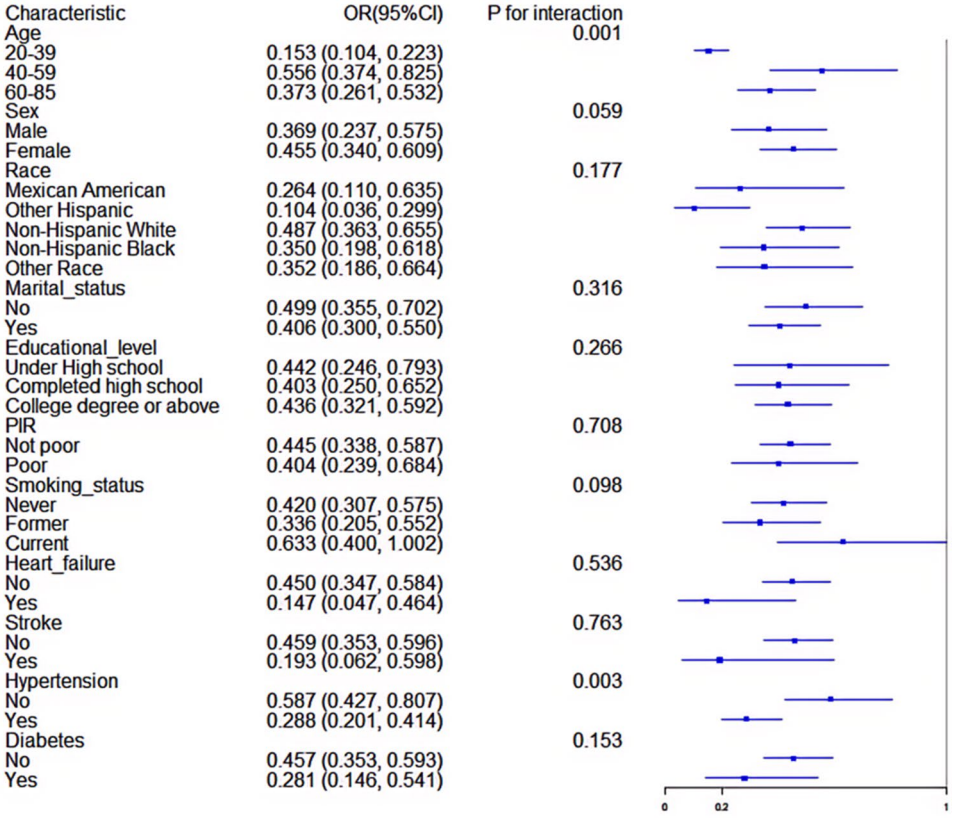

Fig. 3 Subgroup analysis of the association between METS-VF and Osteoporosis

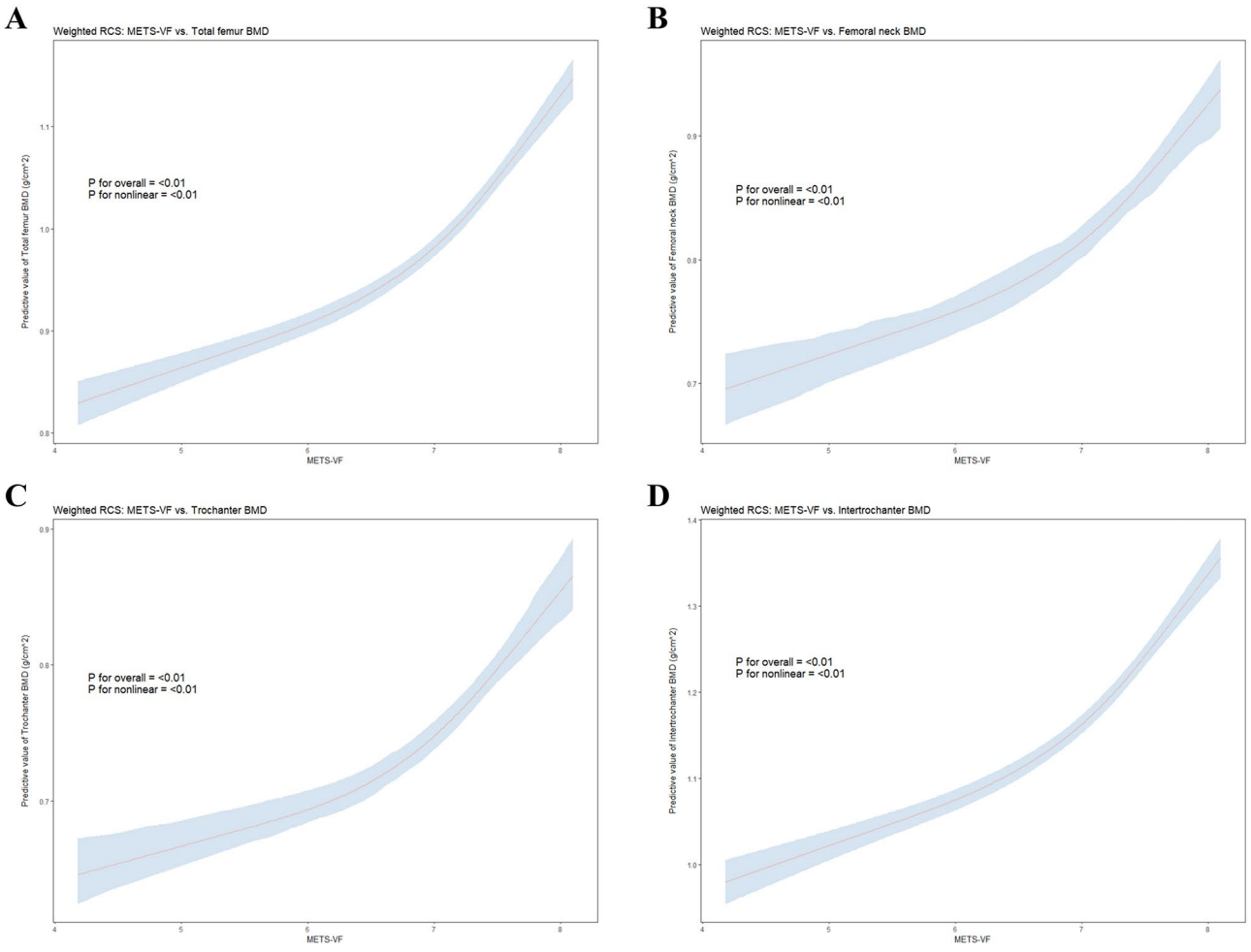

Fig. 4 The non-linear relationship between METS-VF and bone density at different sites. MEC weight was adjusted; For bone mineral density in all areas: age, gender, race, marital status, education level, physical activity, PIR, smoking status, total calcium, uric acid, creatinine, heart failure, stroke, hypertension, diabetes, HEI-2020 and depression were adjusted

and height, unable to distinguish between muscle and fat, nor does it reflect the distribution of fat, especially visceral fat accumulation. For instance, individuals with well-developed muscles may be misclassified as overweight, while those with normal body weight but excessive visceral fat might be overlooked [28]. Simple visceral fat scores (such as waist circumference, BRI) can indicate abdominal fat accumulation but cannot directly assess metabolic abnormalities. For example, some people may have a normal waist circumference but exhibit insulin resistance or lipid abnormalities [29]. It is worth noting that BMI is a static indicator and does not reflect changes in metabolic status over time. This can lead to individuals with a normal BMI but increasing waist circumference developing metabolic abnormalities due to lifestyle changes. In contrast, visceral fat metabolism scores integrate fat distribution and metabolic indicators, providing a more comprehensive reflection of metabolic health. They offer real-time health feedback through dynamic monitoring of biomarkers (such as blood glucose fluctuations and inflammation levels) and predict future disease risks [30]. Some studies have indicated that an increase in visceral fat volume is associated with improved BMD, potentially due to the estrogen and other adipokines secreted by visceral fat, which promote bone formation [31]. However, excessive visceral fat may accelerate bone resorption and reduce BMD by promoting chronic inflammation and hormonal imbalance [32], thereby increasing the risk of osteoporosis. Our study demonstrates that a higher METS-VF index is significantly associated with a reduced risk of osteoporosis, particularly in older individuals and those with hypertension or diabetes. This association may be closely related to metabolic abnormalities and bone metabolism. Studies have shown that insulin resistance is closely related to bone metabolism [33], and insulin resistance and hyperglycemia are known to increase BMD in postmenopausal women without diabetes [34]. Moreover, metabolic syndrome

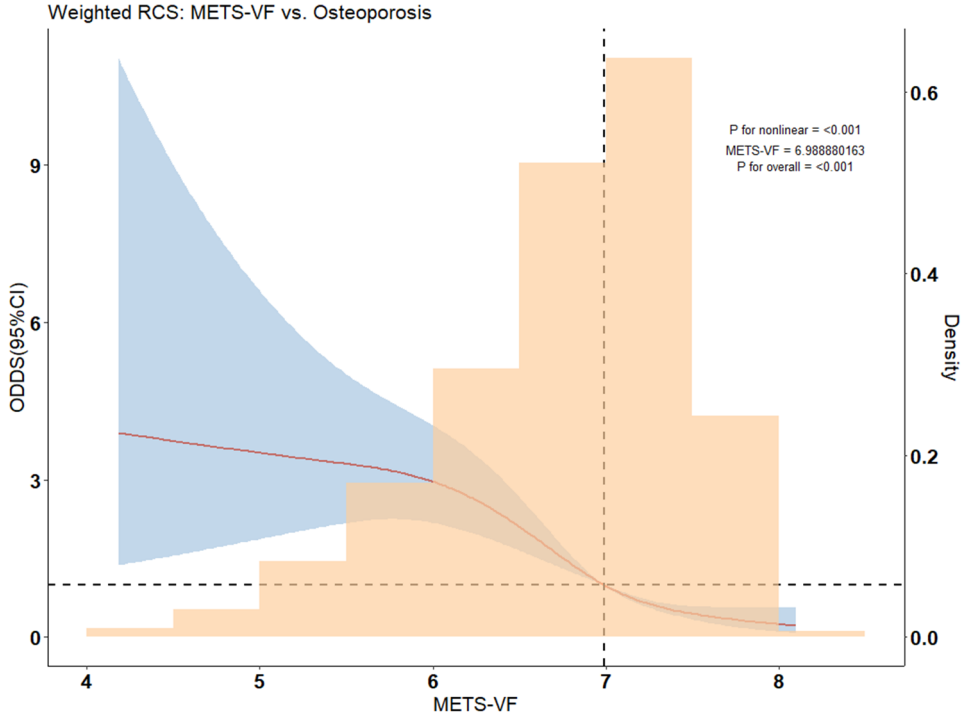

Fig. 5 The non-linear relationship between METS-VF and osteoporosis. MEC weight was adjusted; Age, gender, race, marital status, education level, physical activity, PIR, smoking status, total calcium, uric acid, creatinine, heart failure, stroke, hypertension, diabetes, HEI-2020 and depression were adjusted

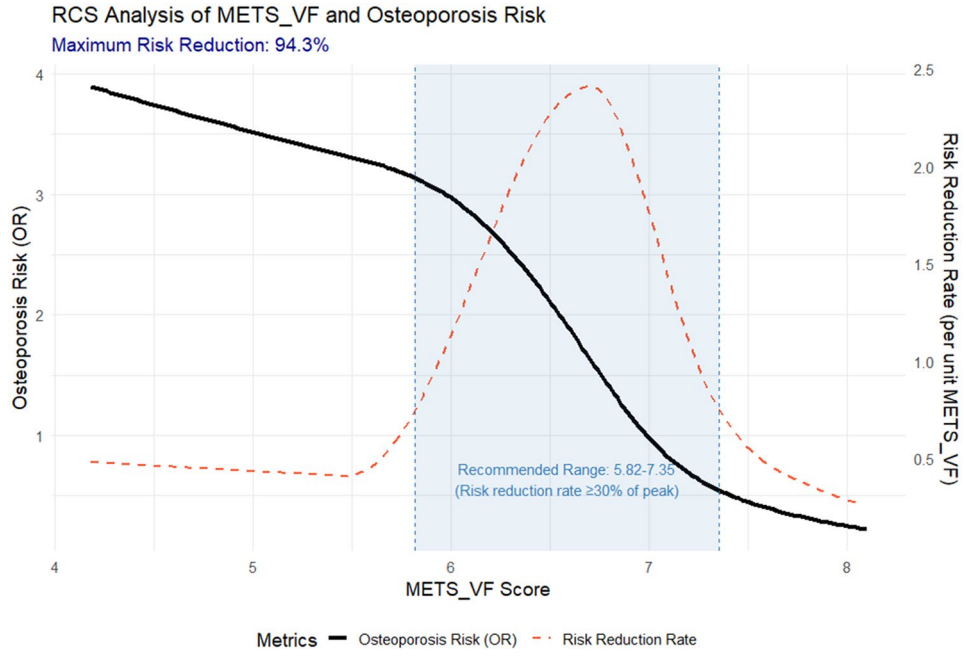

Fig. 6 RCS-Derived METS-VF Reference Intervals for High-Efficacy Osteoporosis Risk Intervention

may influence calcium metabolism and hemodynamics, enhancing BMD [35].

Our study also found that participants with higher METS-VF levels had elevated uric acid and creatinine values, which had a greater impact on BMD and osteoporosis, consistent with previous studies [36, 37]. An increase in visceral fat is often accompanied by weight gain, and moderate weight gain can stimulate bone formation by increasing mechanical load on the skeleton, thus enhancing BMD [10]. However, excessive weight may overload the bones, increasing the risk of fractures [38]. Additionally, obesity-related metabolic abnormalities influence

estrogen secretion [39], and estrogen deficiency is one of the main causes of osteoporosis [40]. The increase in fat may mitigate the negative impact of estrogen deficiency on BMD by converting androgens into estrogens in adipose tissue [35]. Excessive visceral fat, however, may inhibit the normal secretion of sex hormones via a feedback mechanism, further influencing bone metabolism. This bidirectional regulatory effect may explain the nonlinear relationship between METS-VF and BMD and osteoporosis risk.

Despite these dual mechanisms, this study shows that an increase in METS-VF is associated with a reduced risk of osteoporosis, although the effectiveness of this protective effect can vary with changes in METS-VF. Additionally, the potential adverse effects of excess visceral fat are also worth noting [41]. We obtained a reference range for the sensitivity of METS-VF in reducing osteoporosis risk through changes in the slope of the RCS curve (5.82–7.35). Within this range, the benefit of each unit increase in METS-VF in reducing the risk of osteoporosis is relatively higher. Of course, the application of this range in clinical practice requires further judgment based on individual circumstances and clinical diagnosis.Although we were unable to identify the specific threshold for the relationship between METS-VF and BMD and osteoporosis. This may be due to the skewed distribution of visceral fat levels in the sample, especially since there were fewer individuals with excessive visceral fat in certain populations, which affected the ability to identify a clear threshold. The genetic background of different individuals also affects visceral fat distribution and bone metabolism, adding complexity to this relationship. Variations in sex, age, and hormone levels across individuals may influence the relationship between visceral fat and BMD.

Interventions targeting METS-VF, such as improving metabolic syndrome and reducing visceral fat accumulation, could emerge as novel strategies for preventing and managing osteoporosis. Through lifestyle interventions and pharmacological treatments, adjusting METS-VF levels may help improve metabolic health while preserving BMD and reducing osteoporosis risk. Additionally, understanding the nonlinear relationship between METS-VF and bone health could aid in developing personalized treatment plans. For individuals with different METS-VF levels, tailored interventions may maximize the protective effects of visceral fat on bone health while minimizing its potential adverse effects, leading to more precise medical management.

Limitations

We further studies are needed to validate these findings and explore the relationship between METS-VF, BMD, and osteoporosis in greater depth. This study has several key strengths. First, the large sample size ensures high representativeness at the national level. Second, this is the first cross-sectional study in the U.S. population to investigate the relationship between METS-VF, BMD, and osteoporosis. As an integrated measure of metabolism and visceral fat, METS-VF provides a more comprehensive reflection of an individual's metabolic status and visceral fat levels compared to single indicators.

However, this study also has some limitations: First, NHANES aims to represent the adult population of the United States, but this may not be entirely true. Despite its well-designed sampling methods, certain subgroups may still be overlooked. For example, individuals in remote areas or those with specific lifestyle characteristics who are difficult to reach during the survey may be underrepresented. This potential sampling bias could limit the extent to which the study results can be applied to the entire adult population of the United States. Second, the cross-sectional design prevents causal inference, and the temporal relationship between METS-VF and bone health remains unclear. Longitudinal studies are needed to verify causality. Although we adjusted for various confounding factors such as age, sex, race, and lifestyle, diet, genetics, unmeasured confounders may still affect the results, future studies could further assess its applicability in different populations.

Conclusions

In this study, NHANES data were used to examine the potential nonlinear positive correlation between METS-VF and BMD, as well as the possible nonlinear negative correlation with the risk of osteoporosis. This provides new insights into the relationship between METS-VF, BMD, and osteoporosis, offering a novel approach for further evaluating the associations between these variables.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41043-025-00914-2.

Supplementary Material 1

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Data availability
Publicly available datasets were analyzed in this study. This data can be found here: https://www.cdc.gov/nchs/nhanes.

Declarations

Ethical approval
The studies involving human participants were reviewed and approved by The National Center for Health Statistics Research Ethics Review Board. The patients/participants provided their written informed consent to participate in this study. All methods were carried out in accordance with relevant guidelines and regulations (Declaration of Helsinki).

Consent for publication
We, the undersigned authors, hereby declare that we have read and approved the manuscript submitted to Journal of Health, Population and Nutrition. We consent to its publication in this journal.

Competing interests
The authors declare no competing interests.

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