Journal of Health, Population and Nutrition

RESEARCH

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Exploring the impact of protein intake on the association between oxidative balance score and lean mass in adults aged 20–59: NHANES 2011–2018

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Abstract

Background Previous studies have established a correlation between the pathogenesis of oxidative stress and sarcopenia. The Oxidative Balance Score (OBS) is an integrated measure that reflects the overall balance of antioxidants and pro-oxidants in dietary components and lifestyle. However, there are limited reports on the association between OBS and lean mass and the impact of protein intake on the association between OBS and lean mass.

Methods Using data from the National Health and Nutrition Examination Survey from 2011 to 2018, multivariate linear and logistic regression analyses were conducted to explore the associations between OBS and outcomes. The findings were then illustrated through fitted smoothing curves and threshold effect analyses.

Results This study included 2,441 participants, demonstrating that higher OBS is significantly associated with an increased ratio of appendicular lean mass to body mass index. Key inflection points at OBS 31 mark pronounced changes in these associations, with age and protein intake notably affecting the association. The effect of OBS on lean mass varies among populations with high and low protein intake.

Conclusions Our findings suggest that OBS is significantly and positively associated with lean mass. A high protein intake of more than 84.5 g/day may enhance the role of OBS in influencing muscle health to improve muscle outcomes.

Keywords Oxidative Balance Score (OBS), Appendicular Lean Mass (ALM), Sarcopenia, Oxidative stress, NHANES, Protein intake

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Introduction

Sarcopenia represents a progressive, generalized disease affecting skeletal muscles, it is defined by a decline in muscle mass, strength, and function, predominantly observed in elderly populations [1]. Globally, the prevalence of sarcopenia in the general population ranges between 5% and 10% [2]. This disease impacts daily life, increases the risk of falls, and reduces autonomy. Furthermore, sarcopenia has been linked to negative health outcomes associated with several diseases, including bone fractures, osteoporosis, cancer, and diabetes, all of which detrimentally impact human health [3–6]. Skeletal muscle mass is regulated by two tight and dynamic processes: muscle protein synthesis (MPS) and muscle protein breakdown (MPB) [7]. The decrease in muscle mass and the occurrence of sarcopenia are related to numerous factors, including aging, lack of physical activity, neuromuscular dysfunction, negative net protein balance, and changes in several hormones (insulin, sex hormones, thyroid hormones, glucocorticoids) [8–11]. Furthermore, reductions in nutrient intake (including macronutrients and micronutrients) also play a role [9]. For instance, adequate intake of protein, vitamin D, and calcium plays a crucial role in maintaining muscle mass and function [11–13]. In healthy young individuals who consume sufficient daily protein, the duration of negative and positive net muscle protein balance are typically equivalent and consequently, skeletal muscle mass maintains stability [14]. However, in older adults, the efficiency of muscle protein synthesis decreases, and hormonal changes further contribute to prolonged periods of negative muscle protein balance, leading to muscle mass loss. Similarly, individuals who do not consume enough protein experience extended periods of negative muscle-protein balance, which negatively impacts muscle mass and function [12, 13].

Oxidative stress is commonly characterized as an imbalance between the production of antioxidants and the generation of oxidants. This imbalance can result in the formation of toxic free radicals, primarily reactive oxygen species (ROS) and reactive nitrogen species (RNS) [15]. Recent studies have shown that various dietary components, including vitamin C, E, and carotenoids, and non-dietary factors, including cigarette smoking and alcohol consumption, can directly or indirectly affect the balance between antioxidants and pro-oxidants [16]. The Oxidative Balance Score (OBS) serves as a composite indicator reflecting the overall balance between antioxidants and pro-oxidants within one's diet and lifestyle. Mitochondria are abundant in skeletal muscle and play a critical role in producing ROS, which are essential for muscle function and adaptation. The adenosine monophosphate-activated protein kinase (AMPK) pathway contributes significantly to skeletal muscle health by regulating mitochondrial function and ensuring an appropriate balance of ROS production. This balance is crucial as it supports cellular signaling and muscle adaptation processes [17]. However, overproduction of ROS can disrupt this balance, leading to oxidative stress that deteriorates biomolecules and cellular structures. Thioredoxin-interacting protein (TXNIP) has been identified as a key regulator in redox metabolism, and its dysregulation can exacerbate oxidative damage, impacting muscle health and function negatively [18]. Therefore, maintaining oxidative balance in muscle is crucial. Research has shown that whey protein intake enhances oxidative homeostasis and may serve as a potential adjunctive therapeutic tool for diseases associated with oxidative stress, demonstrating immune-enhancing properties possibly linked to increased glutathione synthesis in lymphocytes. For instance, studies in obese Zucker rats indicated that whey protein supplementation at a dosage of approximately 20% of their diet inhibited food intake and improved oxidative balance [19].

Current research shows that OBS and low muscle mass are significantly negatively correlated. Generally, a higher OBS suggests that antioxidants predominate over pro-oxidants [20]. Modulating oxidative balance with an antioxidant-rich diet could prevent low muscle mass [21]. To our knowledge, there are currently no studies investigating the association between protein intake, OBS, and lean mass. Therefore, we conducted this study using NHANES data from 2011 to 2018. We hypothesize that there is a significant positive association between the OBS and muscle mass, and that sufficient protein intake enhances the efficacy of OBS in influencing muscle mass.

Materials and methods

Study population

These analyses utilized data from the National Health and Nutrition Examination Survey (NHANES), as depicted in Fig. 1, which outlines the participant selection methodology. This study utilizes the four survey cycles of data from 2011 to 2018. Initially, 21,230 individuals lacking data on limb lean body mass and 1,113 with incomplete dietary records were excluded. Additionally, 6,537 participants, including those under the age of 20, were omitted from the analysis. Furthermore, we removed 7,835 subjects who were missing other essential variables. Ultimately, the analysis encompassed 2,441 adults with comprehensive datasets. All participants provided written consent, and the study protocol was approved by the Ethics Review Board of the National Center for Health Statistics.

Assessment of oxidative balance score

Building on prior research, the OBS incorporates contributions from four lifestyle and 16 dietary factors,

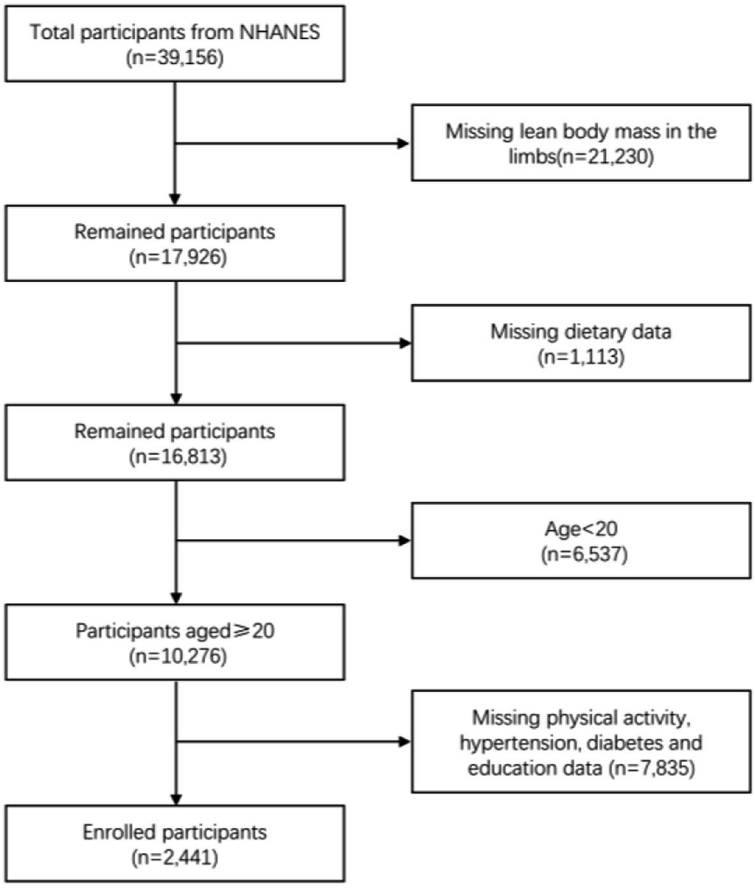

Fig. 1 Flowchart of participant selection

encompassing five pro-oxidants and 15 antioxidants. The OBS quantifies the combined impact of lifestyle and diet from the first 24-hour dietary recall, with higher scores indicating increased antioxidant exposure. Detailed scoring criteria are presented in Table S1: dietary antioxidants are scored from 0 to 2 across the first to third quartiles. At the same time, pro-oxidants receive a score of 2 in the lowest tertile and 0 in the highest. For smoking behavior, we used serum cotinine, a primary metabolite of nicotine with a longer half-life, to gauge tobacco use. This measure reflects smoking behavior more accurately due to its extended presence in the bloodstream [22]. The metabolic equivalent (MET) scores were calculated from data collected by the Physical Activity Questionnaire (PAQ) to quantify energy expenditure. MET values were assigned to categories including vigorous and moderate work-related tasks, transportation activities like walking or bicycling, and vigorous and moderate leisure-time activities. Physical activity levels were determined by multiplying the MET value by the weekly frequency and duration of each activity [23]. For lifestyle factors, physical activity was scored as follows: less than 400 MET minutes per week received 0 points, 400–1,000 MET minutes per week received 1 point, and over 1,000 MET minutes per week received 2 points. Alcohol consumption points were gender-specific. Men scored 0 points for over 30 g per day and 1 point for 0–30 g. Women scored 0 points for over 15 g per day and 1 point for 0–15 g.

Assessment of appendix lean mass and sarcopenia

From 2011 to 2018, participants aged 40–60 underwent Dual-energy X-ray absorptiometry (DEXA) which is a widely used and validated technique for assessing lean mass. The ratio of ALM to body mass index (ALM/BMI) is calculated by dividing the total lean mass of the arms and legs by BMI, which is a key indicator for evaluating lean mass [24]. We excluded individuals who were pregnant, had used barium contrast within the past week, exceeded 450 pounds (204.12 kg) in weight, or were taller than 6 feet 5 inches. For participants meeting the criteria, appendicular lean mass (ALM) was measured as the total lean mass in the limbs minus bone mineral content. Following the guidelines from the Foundation for the National Institutes of Health (FNIH), a non-profit organization that supports the mission of the National Institutes of Health, sarcopenia was diagnosed as ALM adjusted for BMI (<0.789 kg/kg/m^2 for males and <0.512 kg/kg/m^2 for females) [24].

Covariables

To examine the effects of potential confounders, selected covariates included age, gender, race, hypertension, diabetes, family income to poverty ratio (PIR), cancer, sleep disorders, level of education, energy intake (kcal), protein intake (grams), carbohydrate intake (grams), and total fat intake (grams). Methods used for collecting these variables are thoroughly documented in the NHANES Survey Methods and Analysis.

Statistical analysis

For the statistical analyses, we utilized EmpowerStats 4.1 and R software (version 4.2.3). We established statistical significance at a p-value of less than 0.05. We divided the Oxidative Balance Score (OBS) into four quartiles, ranging from the lowest (Q1) to the highest (Q4). Continuous variables were summarized using means and standard deviations (SDs), and categorical variables were presented as proportions. All analyses were conducted using the recommended weighting procedures for NHANES data to ensure representativeness. We used the Rao-Scott chi-square test for categorical variables and one-way ANOVA for continuous variables to account for the complex survey design. Multivariate linear and logistic regression analyses were conducted to explore the associations between OBS and ALM_{BMI} or sarcopenia using three progressive models. Model 1 was unadjusted. Model 2 included adjustments for gender, age, race, and PIR. Model 3 further adjusted for educational attainment, hypertension, diabetes, cancer, sleep disorders, energy intake (kcal), protein intake (grams), carbohydrate intake (grams), and total fat intake (grams). Results were expressed as regression coefficients (β) and odds ratios (OR), both with 95% confidence intervals (CI). After adjusting for all confounders, we utilized smooth curve fitting and threshold effect analysis to assess the relationship between OBS and ALM_{BMI}, aiming to identify critical inflection points. Furthermore, subgroup analyses were executed to investigate the association between OBS and ALM_{BMI} or sarcopenia across various demographics and health statuses. Protein, energy, and carbohydrate intakes were categorized into low and high groups, and we conducted interaction tests to examine the consistency of the associations across these subgroups.

Results

Baseline characteristics of participants

Table 1 presents the characteristics of participants categorized by OBS quartiles. The analysis revealed no significant differences in age among the groups ($p=0.623$), with average ages ranging from 37.83 to 38.66 years. Although the percentage of males decreased from 70.04% in Q1 to 63.95% in Q4, the observed difference in gender distribution did not reach statistical significance ($p=0.051$). Significant disparities were observed in race/ethnicity and educational levels (both $p<0.001$). Health status indicators also varied significantly: the prevalence of hypertension decreased from 27.62% in Q1 to 21.47% in Q4 ($p=0.014$). Cancer prevalence also differed markedly ($p=0.013$), with the lowest percentage observed in Q3 (1.95%). There was no significant difference in the prevalence of diabetes ($p=0.363$). Moreover, there were also significant increases in the PIR from Q1 to Q4 ($p<0.001$), as well as in dietary intake, including energy ($p<0.001$) and macronutrients such as protein and carbohydrates (both $p<0.001$), indicating a clear trend toward higher socioeconomic status and improved dietary intake from Q1 to Q4. Besides, ALM_{BMI} showed a significant difference ($p=0.015$), and sarcopenia's prevalence had a decreasing trend across quartiles.

Relationship between OBS and ALM_{BMI}

Three models were constructed to investigate the association between OBS and ALM_{BMI}, as detailed in Table 2. In Model 3, the regression coefficient (β) was 0.003 (95% CI: 0.003–0.004) with a p-value of less than 0.00001, showing for each unit increase in OBS, ALM_{BMI} increased by 0.003 units. This positive association was also evident in Models 1 and 2. Notably, compared to participants in Quartile 1, those in Quartile 4 of Model 3 exhibited the most substantial increases (β=0.051, 95% CI: 0.033, 0.070, $p<0.00001$). Adjusted smoothed plots suggest a non-linear relationship between OBS and ALM_{BMI} (Fig. 2A). Below an OBS threshold of 31, each unit increase in OBS corresponded to a modest increase in ALM_{BMI} (β=0.003, 95% CI: 0.003, 0.004, $p<0.0001$). Above this threshold, the association became more pronounced (β=0.018, 95% CI: 0.009, 0.026, $p<0.0001$). The inflection at OBS 31 was statistically validated by a log-likelihood ratio of 0.001, indicating a dose-response relationship with stronger effects of OBS on ALM_{BMI} at higher levels (Table 3). Stratification was conducted based on sex, age, protein intake, and total energy intake, as illustrated in Fig. 3. With increasing OBS, ALM_{BMI} exhibited a rise; however, variability in the curve slopes was evident, with notably higher slopes observed in the high-protein group and an inflection point present. Threshold effect analysis conducted for OBS values exceeding 32 revealed a significant escalation in ALM_{BMI} as OBS increased (Table 4). Additionally, among individuals younger than 40 years, a transient plateau was noted around OBS=10 and OBS=23. Yet, for OBS values greater than 30, there was a marked increase in the slope of ALM_{BMI}. The forest plot (Fig. 4) and Table S2 demonstrated a statistically significant interaction between OBS and age, with an enhanced effect observed in participants aged 40 and above ($p=0.0424$). Furthermore, the level of protein intake emerged as a significant moderator

Table 1 The baseline characteristics by quartiles of the OBS: National Health and Nutrition Examination Survey, United States, 2011–2018

	Q1	Q2	Q3	Q4	*P*-value
	< 15	15 to 21	21 to 27	≥ 27	
N	**554**	**582**	**667**	**638**	
Age (years)	37.83 ± 11.51	38.31 ± 11.13	38.66 ± 11.13	38.27 ± 11.46	0.623
Gender					0.051
Male	388 (70.04%)	404 (69.42%)	468 (70.16%)	408 (63.95%)	
Female	166 (29.96%)	178 (30.58%)	199 (29.84%)	230 (36.05%)	
Race/Ethnicity					**< 0.001**
Mexican American	68 (12.27%)	78 (13.40%)	142 (21.29%)	146 (22.88%)	
Other Hispanic	55 (9.93%)	55 (9.45%)	77 (11.54%)	70 (10.97%)	
Non-Hispanic White	214 (38.63%)	264 (45.36%)	266 (39.88%)	259 (40.60%)	
Non-Hispanic Black	149 (26.90%)	130 (22.34%)	119 (17.84%)	98 (15.36%)	
Other Race - Including Multi-Racial	68 (12.27%)	55 (9.45%)	63 (9.45%)	65 (10.19%)	
Educational level					**< 0.001**
Less than 9th grade	30 (5.42%)	30 (5.15%)	49 (7.35%)	40 (6.27%)	
9-11th grade	108 (19.49%)	76 (13.06%)	93 (13.94%)	74 (11.60%)	
High school grad/GED	167 (30.14%)	168 (28.87%)	195 (29.24%)	172 (26.96%)	
Some college or associate degree	199 (35.92%)	225 (38.66%)	229 (34.33%)	232 (36.36%)	
College graduate or above	50 (9.03%)	83 (14.26%)	101 (15.14%)	120 (18.81%)	
Hypertension					**0.014**
Yes	153 (27.62%)	161 (27.66%)	150 (22.49%)	137 (21.47%)	
No	401 (72.38%)	421 (72.34%)	517 (77.51%)	501 (78.53%)	
Diabetes					0.363
Yes	33 (5.96%)	44 (7.56%)	36 (5.40%)	35 (5.49%)	
No	521 (94.04%)	538 (92.44%)	631 (94.60%)	603 (94.51%)	
Cancer					**0.013**
Yes	30 (5.42%)	20 (3.44%)	13 (1.95%)	25 (3.92%)	
No	524 (94.58%)	562 (96.56%)	654 (98.05%)	613 (96.08%)	
Sleep disorder					0.067
Yes	144 (25.99%)	135 (23.20%)	131 (19.64%)	142 (22.26%)	
No	410 (74.01%)	447 (76.80%)	536 (80.36%)	496 (77.74%)	
Family PIR	1.94 ± 1.39	2.36 ± 1.49	2.32 ± 1.49	2.26 ± 1.48	**< 0.001**
Energy intake(kcal)	1598.56 ± 637.52	2088.48 ± 731.58	2681.99 ± 902.38	3359.71 ± 1281.97	**< 0.001**
Protein intake (g)	52.11 ± 23.61	74.67 ± 27.84	100.59 ± 35.47	133.59 ± 54.06	**< 0.001**
Carbohydrate intake (g)	194.85 ± 92.64	251.22 ± 107.50	313.80 ± 126.24	395.78 ± 162.94	**< 0.001**
ALM_{BMI}	0.86 ± 0.20	0.86 ± 0.19	0.88 ± 0.20	0.88 ± 0.20	**0.015**
Sarcopenia					0.412
Yes	47 (8.48%)	50 (8.59%)	57 (8.55%)	41 (6.43%)	
No	507 (91.52%)	532 (91.41%)	610 (91.45%)	597 (93.57%)	

Data were expressed as mean ± standard deviations or counts (weighted percentages). GED: general equivalent diploma; PIR: family income to poverty ratio. ALM_{BMI}: appendicular lean mass to body mass index

(p = 0.0006), suggesting variability in the influence of OBS on protein consumption. No significant interactions were identified for gender, hypertension, diabetes, cancer, sleep disorders, or intake of carbohydrates and energy.

Relationship between OBS and Sarcopenia

As shown in Table 5, the association between OBS and sarcopenia was statistically significant in Model 2, with an odds ratio (OR) of 0.960 (95% CI: 0.939, 0.982), suggesting a reduced risk of sarcopenia with higher OBS levels. However, in Model 3, this association was not significant (OR = 0.981, 95% CI: 0.948, 1.016). Sensitivity analyses using OBS quartiles showed that participants in the highest quartile (Q4) experienced a significant reduction in sarcopenia risk in Model 2 (OR = 0.493, 95% CI: 0.310, 0.784), while in Model 3, the risk reduction was not statistically significant (OR = 0.794, 95% CI: 0.412, 1.530), compared to participants in Q1. Threshold effect analysis revealed a distinct inflection point at an OBS of 27 (Fig. 2B; Table 6), above which each incremental unit of OBS was associated with a significant 16% decrease in sarcopenia risk. Conversely, below this OBS threshold,

Table 2 The association between OBS and ALM_{BMI}

	Model 1		Model 2		Model 3	
	β (95%CI)	*P*-value	β (95%CI)	*P*-value	β (95%CI)	*P*-value
OBS (continuous)	**0.002 (0.001, 0.003)**	**0.00388**	**0.004 (0.003, 0.004)**	**< 0.00001**	**0.003 (0.003, 0.004)**	**< 0.00001**
OBS (quartile)						
Q1	reference		reference		reference	
Q2	0.002 (-0.022, 0.025)	0.89343	0.005 (-0.008, 0.019)	0.41286	0.003 (-0.011, 0.016)	0.67473
Q3	0.027 (0.004, 0.049)	**0.01986**	0.041 (0.028, 0.054)	**< 0.00001**	0.033 (0.018, 0.047)	**0.00001**
Q4	0.027 (0.004, 0.049)	**0.02018**	0.065 (0.052, 0.077)	**< 0.00001**	0.051 (0.033, 0.070)	**< 0.00001**

Model 1 is not adjusted for any variables

Model 2 adjusts for the following variables: Age, Gender, Race, and Poverty Income Ratio (PIR)

Model 3 builds upon Model 2 by adding additional covariates including: Educational Level, Hypertension, Diabetes, Cancer, Sleep Disorder, Energy Intake (kcal), Protein Intake (grams), Carbohydrate Intake (grams), and Total Fat Intake (grams). OBS: Oxidative Balance Score. $p < 0.05$ was considered statistically significant

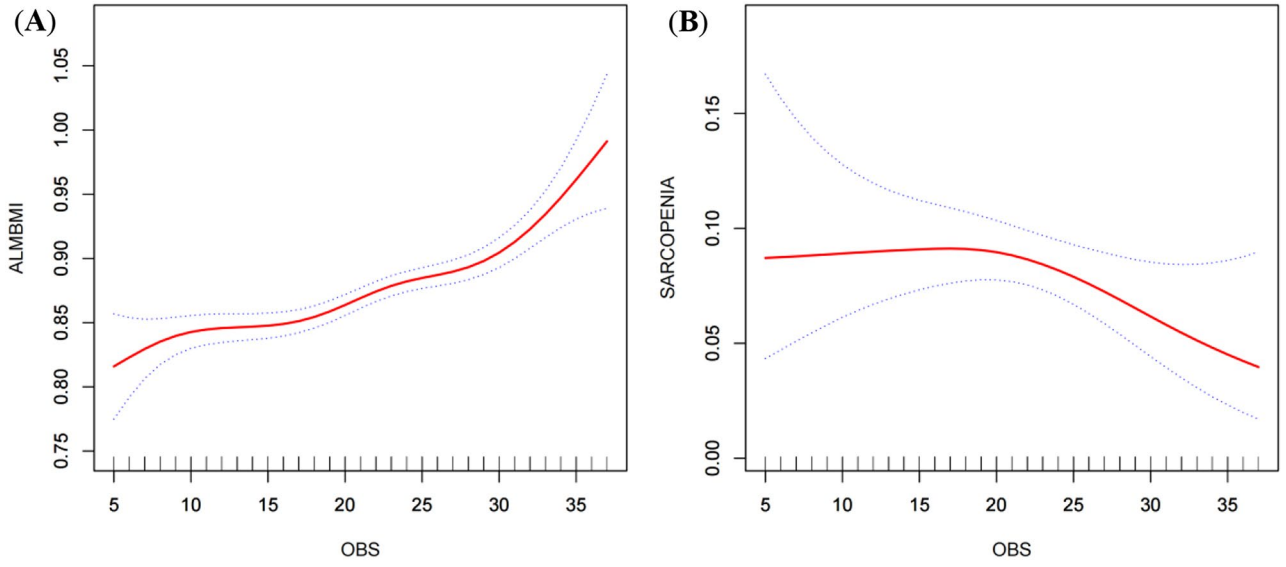

Fig. 2 The dose-response relationship between OBS and ALM_{BMI} (**A**) and sarcopenia (**B**)

Table 3 Threshold effect analysis of OBS on ALM_{BMI} by the two-piecewise linear regression

Inflection point	Adjusted β (95% CI)	*P*-value
< 31	0.003 (0.003, 0.004)	**< 0.0001**
≥ 31	0.018 (0.009, 0.026)	**< 0.0001**
Log-likelihood ratio	**0.001**	

the association was not statistically significant. Table S3 displays the outcomes of the interaction analysis. However, no significant interactions were found for age, gender, hypertension, diabetes, cancer, sleep disorders, or intake of carbohydrates, protein, and energy.

Discussion

Two thousand four hundred forty-one participants were included in these cross-sectional analyses. We observed a positive association between OBS and ALM_{BMI}. In addition, this association suggests that increasing OBS may reduce the risk of sarcopenia. Results from subgroup analysis and interaction tests found a significant interaction on age and protein intake regarding this association. Our results suggest that dietary intake and lifestyle adjustments aimed at managing OBS could potentially improve muscle quality and reduce the risk of sarcopenia. Increasing protein intake may enhance OBS, leading to improvements in lean mass.

Prior studies have demonstrated that oxidative stress is critical in developing inflammation-induced skeletal muscle dysfunction [25], which involves initiating the pro-inflammatory nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kB) signaling pathway, promoting neutrophil infiltration, and creating an inflammatory environment that facilitates muscle atrophy induction [26–29]. Similarly, in a recent study, increased systemic immune inflammation index (SII) levels, an indicator reflecting both the immune response and the systemic inflammatory response, were linked to an increased risk of low muscle mass [30]. In addition, a recent study showed that the Composite Dietary Antioxidant Index (CDAI) includes several dietary antioxidants, including vitamin C, vitamin E, beta-carotene, and selenium. This study found that in men, CDAI was

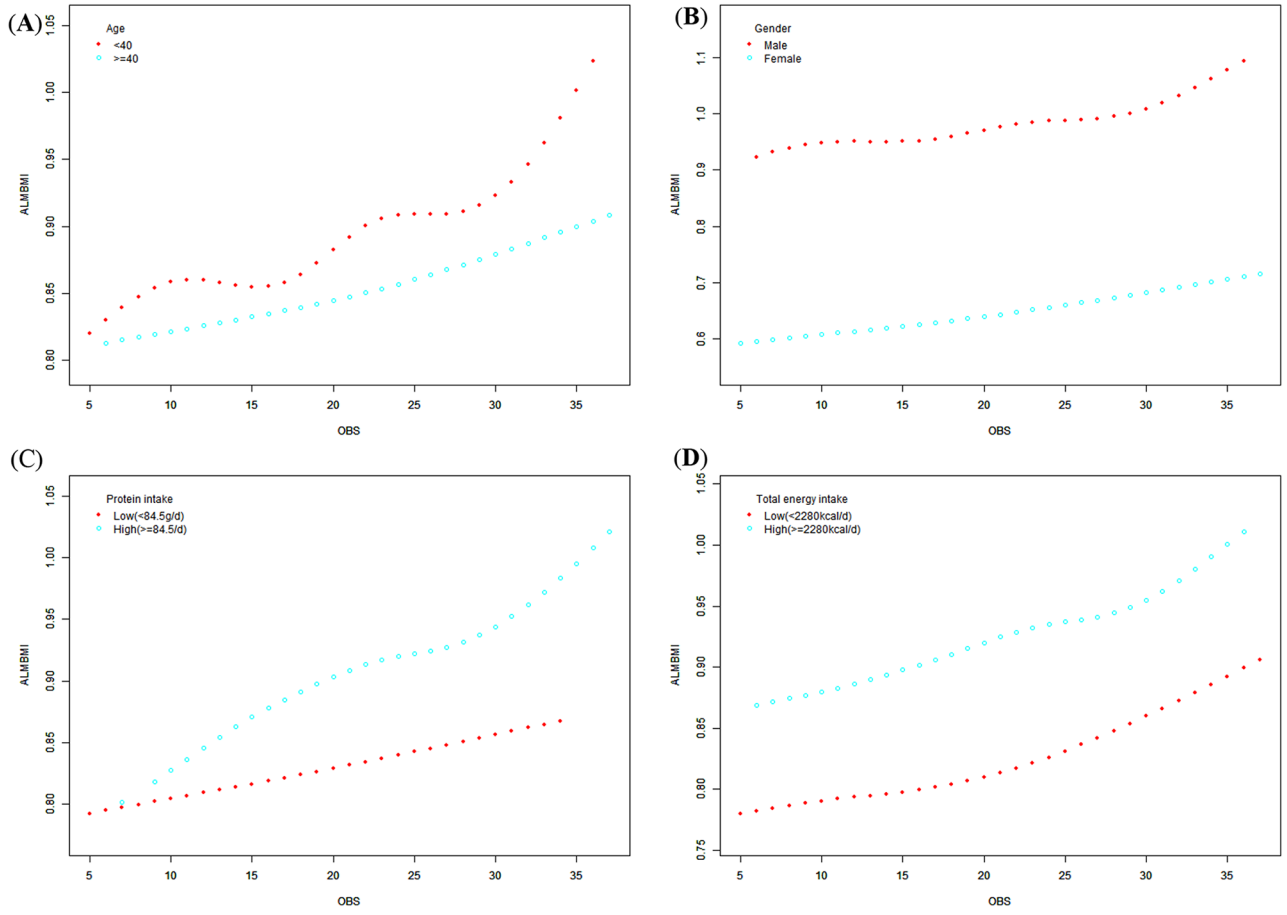

Fig. 3 Stratified analysis of the dose-response relationship between OBS and ALM_{BMI}. (**A**) Stratified by sex (**B**) Stratified by age (**C**) Stratified by protein intake (g/kg/d). (**D**) Stratified by total energy intake. Confounders were adjusted for Age, Gender, Race, PIR, Educational level, Hypertension, Diabetes, Cancer, Sleep Disorder, Energy Intake (kcal), Protein Intake (grams), Carbohydrate Intake (grams), and Total Fat Intake (grams). In the subgroup analyses, the models were not adjusted for the stratification variables themselves

Table 4 Threshold effect analysis of OBS on ALM_{BMI} stratified by protein intake

	Inflection point	Adjusted β (95% CI)	*P*-value
Low protein intake (< 84.5 g/d)	None	0.003 (0.002, 0.005)	**< 0.0001**
High protein intake (≥ 84.5/d)	< 32	0.004 (0.003, 0.006)	**< 0.0001**
	≥32	0.023 (0.008, 0.037)	**0.0025**
	Log-likelihood ratio	**0.016**	

significantly positively associated with handgrip strength (HGS), specifically, each unit increase in CDAI was associated with a 0.015 unit increase in HGS (30). Moreover, a study conducted by Van Dronkelaar et al. demonstrated that selenium, which is an essential potential antioxidant, has a positive relationship with muscle strength [31]. Furthermore, Owen J. Kelly et al. found that consuming an excess of high glycemic index (GI) foods, defined as those with a GI value over 70 and comprising more than 50% of daily caloric intake, as well as a lower protein intake, defined as less than 0.8 g of protein per kilogram of body weight per day, may contribute to sarcopenic obesity [32]. The OBS is an integrated measure that reflects the overall balance of antioxidants and pro-oxidants in dietary components and lifestyle. Its calculation involves 20 variables, including well-known antioxidants such as selenium, vitamins A, E, and C, alongside lifestyle habits like alcohol and tobacco consumption, as well as physical activity [33]. This comprehensive approach aids in obtaining a more precise indicator of overall oxidative balance and proves its application effectiveness and advantages in clinical studies.

The study further investigated OBS quartiles and determined that OBS increases within specific ranges. Based on previous studies, we included various control variables such as age, gender, race, common health conditions, and macronutrient intake, which could influence the research results [34]. It highlights a positive correlation between OBS levels and lean mass. Notably, adjusted smoothed plots reveal a non-linear relationship between OBS and ALM_{BMI} (Fig. 2a). Before and after the threshold ($\beta = 0.003$, $p < 0.0001$; $\beta = 0.018$, $p < 0.0001$), the sixfold

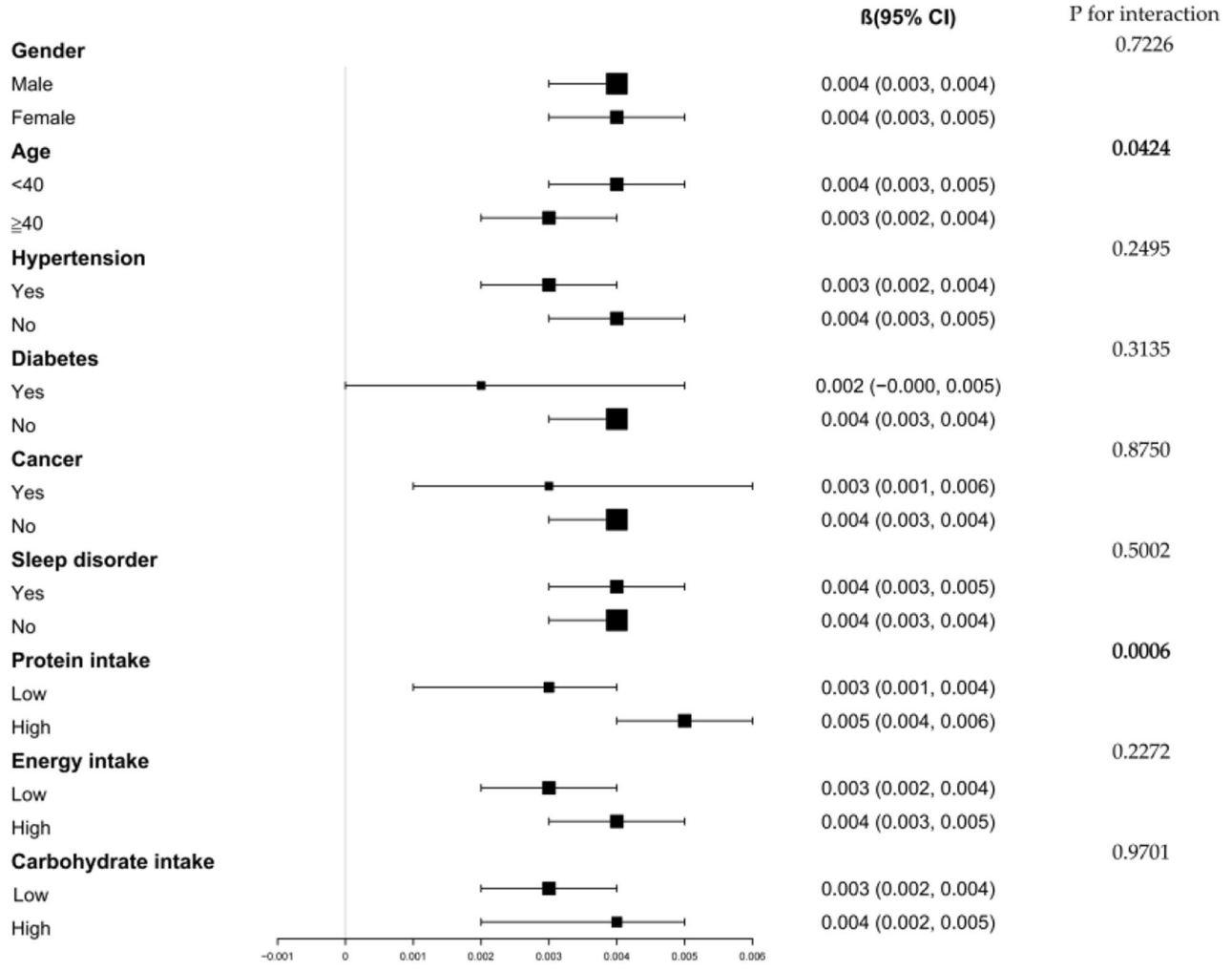

Fig. 4 An analysis of OBS and ALM_{BMI} stratified by baseline characteristics

Table 5 The association between OBS and Sarcopenia

	Model 1		Model 2		Model 3	
	OR (95%CI)	***P*-value**	**OR (95%CI)**	***P*-value**	**OR (95%CI)**	***P*-value**
OBS (continuous)	**0.984 (0.965, 1.005)**	**0.13455**	**0.960 (0.939, 0.982)**	**0.00035**	**0.981 (0.948, 1.016)**	**0.28416**
OBS (quartile)						
Q1	reference		reference		reference	
Q2	1.014 (0.669, 1.537)	0.94842	0.972 (0.626, 1.509)	0.89895	1.103 (0.692, 1.758)	0.68059
Q3	1.008 (0.673, 1.509)	0.96919	0.736 (0.477, 1.134)	0.16454	0.987 (0.585, 1.664)	0.95974
Q4	0.741 (0.479, 1.145)	0.17674	0.493 (0.310, 0.784)	**0.00279**	0.794 (0.412, 1.530)	0.49123

Model 1 is not adjusted for any variables

Model 2 adjusts for the following variables: Age, Gender, Race, and Poverty Income Ratio (PIR)

Model 3 builds upon Model 2 by adding additional covariates including: Educational Level, Hypertension, Diabetes, Cancer, Sleep Disorder, Energy Intake (kcal), Protein Intake (grams), Carbohydrate Intake (grams), and Total Fat Intake (grams). OBS: Oxidative Balance Score. $p<0.05$ was considered statistically significant

Table 6 Threshold effect analysis of OBS on Sarcopenia by the two-piecewise linear regression

Inflection point	Adjusted OR (95% CI)	*P*-value
< 27	1.000 (0.963, 1.040)	0.9811
≥ 27	0.840 (0.730, 0.968)	**0.0157**
Log-likelihood ratio	**0.018**	

difference in effect sizes suggests a process from quantitative change to qualitative change. Similarly, it was found that beyond an OBS score of 27, each additional unit of OBS was linked to a notable 16% decrease in sarcopenia risk. However, statistical significance was not found below this OBS threshold. These findings align

with prior research indicating that enhancing dietary antioxidant intake and lowering prooxidant intake contributes to enhancing muscle strength [35]. Furthermore, some studies indicate that while moderate levels of ROS produced during exercise may be beneficial for adaptation and health, excessive supplementation of antioxidants could potentially weaken these positive effects [36]. Additionally, other research shows that while antioxidants like N-acetyl cysteine can enhance endurance and reduce fatigue in some cases, high doses may not necessarily improve exercise performance and could interfere with the body's natural beneficial responses to exercise stress [37]. Another review emphasizes that although dietary antioxidants such as polyphenols and vitamins can potentially reduce the oxidative stress and inflammation caused by intense exercise, excessive intake might impede the body's adaptive responses to exercise training, possibly diminishing benefits in performance or recovery. Therefore, antioxidants require careful regulation [38].

Interestingly, subgroup analysis revealed significant variations in the relationship between OBS and ALM_{BMI} concerning age and protein intake. The results are partially consistent with previous studies [39]. The impact of OBS on lean mass was notably greater when protein intake exceeded 84.5 g/day and when OBS ≥ 32. Similarly, numerous studies have explored the impact of protein intake on lean mass. Stephanie M. Fanelli et al. demonstrated physical limitations linked to low protein intake. Additionally, low protein intake is associated with an elevated risk of muscle loss [40]. A cross-sectional study conducted in China showed an association between fat intake and muscle mass when protein intake surpassed 1.7 g/kg/day [41]. These findings highlight the significant role of protein intake in preserving muscle mass. Plasma levels of nicotinamide adenine dinucleotide (NAD+) and total nicotinamide adenine dinucleotide (NAD(H)) serve as crucial markers for cellular energy metabolism and redox status, playing a role in regulating intracellular redox reactions and maintaining cellular energy balance [42]. A study conducted in a healthy middle-aged cohort revealed a decrease in plasma NAD+and total NAD(H) levels associated with higher protein intake. As plasma levels of urea, a protein breakdown product, increased, the plasma concentrations of the inflammatory cytokines interleukin-6, kynurenine, and tryptophan also rose [43]. Our study found that the effect of the OBS on lean mass varies among populations with high and low protein intake. Furthermore, research into OBS can support the promotion of plant-based diets. Plant-based diets are rich in antioxidants such as vitamins C and E, polyphenols, and carotenoids, which help neutralize free radicals and reduce oxidative stress [44]. Polyphenols and flavonoids in plant-based diets can enhance the activity of antioxidant enzymes, helping to maintain oxidative balance. High fiber intake also promotes gut health [45]. Future research should include more considerations of plant-based diets and elucidate the mechanism underlying the association between protein metabolism and OBS.

Our study's strength lies in concurrently assessing multiple dietary and lifestyle factors linked to the oxidative aspects of sarcopenia and examining the role of protein intake in OBS's impact on lean mass. Additionally, the reliability and representativeness of our study results were enhanced by a sizable sample size and suitable covariate adjustment. However, our study has some limitations. Firstly, the cross-sectional design prohibits identifying causation, which requires prospective studies to elucidate causality. Besides, the NHANES database does not record all covariates impacting oxidative stress, such as exposure to environmental pollutants and dietary flavonoid consumption. The interaction between inflammation and disease is complex. Furthermore, one notable limitation of this study is the gender imbalance within the study population. Approximately 68% of the participants were male, who typically have higher energy, protein, and antioxidant intakes, as well as greater muscle mass. This demographic skew could influence the study outcomes, as men and women have different metabolic rates, hormonal profiles, and muscle mass, which can affect their response to dietary interventions, including antioxidant supplementation. Consequently, future studies should strive to include a more balanced gender distribution to better understand the differential impacts of antioxidant supplementation across diverse populations. Despite this limitation, we observed a consistent correlation between lean mass and OBS, with the level of protein intake being an important moderator. This highlights the significance of our study in assessing the effect of oxidative balance status on lean mass. These findings can provide valuable guidance for future dietary and lifestyle interventions.

Conclusions

Our results suggest a noteworthy positive relationship between OBS and lean mass. A high protein intake exceeding 84.5 g/day enhances the efficacy of OBS in influencing muscle health for improved muscular outcomes. Further prospective studies are necessary to validate these findings.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41043-024-00629-w.

Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Acknowledgements
We express our gratitude to the personnel at the National Center for Health Statistics of the Centers for Disease Control for their efforts in de-signing, collecting, and compiling the NHANES data, as well as for establishing the public database.

Author contributions
J.-Q.H. and F.-J.H. collected the data. J.-W.Z and Y.-J.Z. analyzed and interpreted. J.-Q.H and S.-Y.H. wrote the main manuscript text. J.-Q.H., Z.-X.Z, and R.W. designed the study. M.-J.W. and W.Z. critically reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding
This research was supported by the Key Research Projects of the Department of Science and Technology of Sichuan Province, China, under Grant NO.2022YFS0164,2023YFS0176.

Data availability
The NHANES data utilized in this study are accessible to the public and can be obtained from the following link: https://www.cdc.gov/nchs/nhanes.

Declarations

Institutional review board statement
The study adhered to the principles outlined in the Declaration of Helsinki and received approval from the Institutional Review Board of the National Centre for Health Statistics.

Informed consent
All participants provided informed consent before enrollment.

Competing interests
The authors declare no competing interests.

Received: 22 May 2024 / Accepted: 20 August 2024
Published online: 02 September 2024

References

1. Sayer AA, Cruz-Jentoft A. Sarcopenia definition, diagnosis and treatment: consensus is growing. Age Ageing. 2022;51(10).
2. Golabi P, Gerber L, Paik JM, Deshpande R, de Avila L, Younossi ZM. Contribution of Sarcopenia and physical inactivity to mortality in people with non-alcoholic fatty liver disease. JHEP Reports: Innov Hepatol. 2020;2(6):100171.
3. Wiedmer P, Jung T, Castro JP, Pomatto LCD, Sun PY, Davies KJA, et al. Sarcopenia - Molecular mechanisms and open questions. Ageing Res Rev. 2021;65:101200.
4. Papadopoulou SK, Papadimitriou K, Voulgaridou G, Georgaki E, Tsotidou E, Zantidou O et al. Exercise and Nutrition Impact on osteoporosis and Sarcopenia-the incidence of Osteosarcopenia: a narrative review. Nutrients. 2021;13(12).
5. Xiang S, Li Y, Li Y, Zhang J, Pan W, Lu Y, et al. Increased Dietary Niacin Intake improves muscle strength, Quality, and glucose homeostasis in adults over 40 years of age. J Nutr Health Aging. 2023;27(9):709–18.
6. Qiao YS, Chai YH, Gong HJ, Zhuldyz Z, Stehouwer CDA, Zhou JB, et al. The Association between Diabetes Mellitus and Risk of Sarcopenia: accumulated evidences from Observational studies. Front Endocrinol. 2021;12:782391.
7. Rogeri PS, Zanella R Jr., Martins GL, Garcia MDA, Leite G, Lugaresi R et al. Strategies to prevent Sarcopenia in the aging process: role of protein intake and Exercise. Nutrients. 2021;14(1).
8. Kim D, Wijarnpreecha K, Sandhu KK, Cholankeril G, Ahmed A. Sarcopenia in nonalcoholic fatty liver disease and all-cause and cause-specific mortality in the United States. Liver International: Official J Int Association Study Liver. 2021;41(8):1832–40.
9. Jyväkorpi SK, Urtamo A, Kivimäki M, Strandberg TE. Macronutrient composition and sarcopenia in the oldest-old men: the Helsinki businessmen Study (HBS). Clinical nutrition (Edinburgh. Scotland). 2020;39(12):3839–41.
10. Bossi P, Delrio P, Mascheroni A, Zanetti M. The Spectrum of Malnutrition/Cachexia/Sarcopenia in Oncology according to different Cancer types and settings: a narrative review. Nutrients. 2021;13(6).
11. Dhillon RJ, Hasni S. Pathogenesis and management of Sarcopenia. Clin Geriatr Med. 2017;33(1):17–26.
12. Morgan PT, Witard OC, Højfeldt G, Church DD, Breen L. Dietary protein recommendations to support healthy muscle ageing in the 21st century and beyond: considerations and future directions. The Proceedings of the Nutrition Society. 2023:1–14.
13. Nishimura Y, Højfeldt G, Breen L, Tetens I, Holm L. Dietary protein requirements and recommendations for healthy older adults: a critical narrative review of the scientific evidence. Nutr Res Rev. 2023;36(1):69–85.
14. Devries MC, Phillips SM. Supplemental protein in support of muscle mass and health: advantage whey. J Food Sci. 2015;80(Suppl 1):A8–15.
15. Xu H, Ranjit R, Richardson A, Van Remmen H. Muscle mitochondrial catalase expression prevents neuromuscular junction disruption, atrophy, and weakness in a mouse model of accelerated Sarcopenia. J cachexia Sarcopenia Muscle. 2021;12(6):1582–96.
16. Xu Z, Lei X, Chu W, Weng L, Chen C, Ye R. Oxidative balance score was negatively associated with the risk of metabolic syndrome, metabolic syndrome severity, and all-cause mortality of patients with metabolic syndrome. Front Endocrinol. 2023;14:1233145.
17. Yan Y, Li M, Lin J, Ji Y, Wang K, Yan D, et al. Adenosine monophosphate activated protein kinase contributes to skeletal muscle health through the control of mitochondrial function. Front Pharmacol. 2022;13:947387.
18. Kokubo K, Hirahara K, Kiuchi M, Tsuji K, Shimada Y, Sonobe Y, et al. Thioredoxin-interacting protein is essential for memory T cell formation via the regulation of the redox metabolism. Proc Natl Acad Sci USA. 2023;120(2):e2218345120.
19. Sukkar SG, Traverso N, Furfaro AL, Tasso B, Marengo B, Domenicotti C, et al. Whey proteins inhibit food intake and tend to improve oxidative balance in obese zucker rats. Eat Weight Disorders: EWD. 2021;26(8):2453–61.
20. Zhang W, Peng SF, Chen L, Chen HM, Cheng XE, Tang YH. Association between the oxidative balance score and telomere length from the National Health and Nutrition Examination Survey 1999–2002. Oxidative medicine and cellular longevity. 2022;2022:1345071.
21. Chen K, Yin Q, Guan J, Yang J, Ma Y, Hu Y, et al. Association between the oxidative balance score and low muscle mass in middle-aged US adults. Front Nutr. 2024;11:1358231.
22. Rebagliato M. Validation of self reported smoking. J Epidemiol Commun Health. 2002;56(3):163–4.
23. Tian X, Xue B, Wang B, Lei R, Shan X, Niu J et al. Physical activity reduces the role of blood cadmium on depression: A cross-sectional analysis with NHANES data. Environmental pollution (Barking, Essex: 1987). 2022;304:119211.
24. Studenski SA, Peters KW, Alley DE, Cawthon PM, McLean RR, Harris TB et al. The FNIH sarcopenia project: rationale, study description, conference recommendations, and final estimates. The journals of gerontology Series A, Biological sciences and medical sciences. 2014;69(5):547 – 58.
25. Zhang H, Qi G, Wang K, Yang J, Shen Y, Yang X, et al. Oxidative stress: roles in skeletal muscle atrophy. Biochem Pharmacol. 2023;214:115664.
26. Ma W, Zhang R, Huang Z, Zhang Q, Xie X, Yang X, et al. PQQ ameliorates skeletal muscle atrophy, mitophagy and fiber type transition induced by denervation via inhibition of the inflammatory signaling pathways. Annals Translational Med. 2019;7(18):440.
27. Wu C, Tang L, Ni X, Xu T, Fang Q, Xu L, et al. Salidroside attenuates Denervation-Induced skeletal muscle atrophy through negative regulation of pro-inflammatory cytokine. Front Physiol. 2019;10:665.
28. Wan Q, Zhang L, Huang Z, Zhang H, Gu J, Xu H, et al. Aspirin alleviates denervation-induced muscle atrophy via regulating the Sirt1/PGC-1α axis and STAT3 signaling. Annals Translational Med. 2020;8(22):1524.
29. Ma W, Xu T, Wang Y, Wu C, Wang L, Yang X, et al. The role of inflammatory factors in skeletal muscle injury. Biotarget. 2018;2:7.
30. Shi L, Zhang L, Zhang D, Chen Z. Association between systemic immune-inflammation index and low muscle mass in US adults: a cross-sectional study. BMC Public Health. 2023;23(1):1416.
31. van Dronkelaar C, van Velzen A, Abdelrazek M, van der Steen A, Weijs PJM, Tieland M, Minerals. The role of Calcium, Iron, Magnesium, Phosphorus, Potassium, Selenium, Sodium, and zinc on muscle Mass, muscle strength, and physical performance in older adults: a systematic review. J Am Med Dir Assoc. 2018;19(1):6–e113.
32. Kelly OJ, Gilman JC, Kim Y, Ilich JZ. Macronutrient intake and distribution in the etiology, Prevention and Treatment of Osteosarcopenic Obesity. Curr Aging Sci. 2017;10(2):83–105.

33. Liu X, Liu X, Wang Y, Zeng B, Zhu B, Dai F. Association between depression and oxidative balance score: National Health and Nutrition Examination Survey (NHANES) 2005–2018. J Affect Disord. 2023;337:57–65.
34. Tomova GD, Arnold KF, Gilthorpe MS, Tennant PWG. Adjustment for energy intake in nutritional research: a causal inference perspective. Am J Clin Nutr. 2022;115(1):189–98.
35. Sahni S, Dufour AB, Fielding RA, Newman AB, Kiel DP, Hannan MT, et al. Total carotenoid intake is associated with reduced loss of grip strength and gait speed over time in adults: the Framingham offspring study. Am J Clin Nutr. 2021;113(2):437–45.
36. Powers SK, Nelson WB, Hudson MB. Exercise-induced oxidative stress in humans: cause and consequences. Free Radic Biol Med. 2011;51(5):942–50.
37. Braakhuis AJ, Hopkins WG. Impact of Dietary antioxidants on Sport performance: a review. Sports Med (Auckland NZ). 2015;45(7):939–55.
38. McLeay Y, Stannard S, Houltham S, Starck C. Dietary thiols in exercise: oxidative stress defence, exercise performance, and adaptation. J Int Soc Sports Nutr. 2017;14:12.
39. Yang W, Gui Q, Chen L, Xu K, Xu Z. Associations between dietary protein and vitamin intake and the physical functioning of older adults with Sarcopenia. Eur Geriatr Med. 2018;9(3):311–20.
40. Fanelli SM, Kelly OJ, Krok-Schoen JL, Taylor CA. Low protein intakes and poor Diet Quality Associate with Functional limitations in US adults with diabetes: a 2005–2016 NHANES Analysis. Nutrients. 2021;13(8).
41. Kwon YJ, Kim HS, Jung DH, Kim JK. Cluster analysis of nutritional factors associated with low muscle mass index in middle-aged and older adults. Clinical nutrition (Edinburgh. Scotland). 2020;39(11):3369–76.
42. Covarrubias AJ, Perrone R, Grozio A, Verdin E. NAD(+) metabolism and its roles in cellular processes during ageing. Nat Rev Mol Cell Biol. 2021;22(2):119–41.
43. Seyedsadjadi N, Berg J, Bilgin AA, Braidy N, Salonikas C, Grant R. High protein intake is associated with low plasma NAD + levels in a healthy human cohort. PLoS ONE. 2018;13(8):e0201968.
44. Trautwein EA, McKay S. The role of Specific Components of a plant-based Diet in Management of Dyslipidemia and the Impact on Cardiovascular Risk. Nutrients. 2020;12(9).
45. Blumfield M, Mayr H, De Vlieger N, Abbott K, Starck C, Fayet-Moore F et al. Should We 'Eat a Rainbow'? An Umbrella Review of the Health Effects of Colorful Bioactive Pigments in Fruits and Vegetables. Molecules. 2022;27(13).

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