He et al. BMC Public Health (2025) 25:1068
https://doi.org/10.1186/s12889-025-22245-x

BMC Public Health

RESEARCH Open Access

Association of dietary health indices with frailty

Ting He[1†], Yifei Yan[2], Dongdong Wang[4], Tingting Peng[3*] and Liuyin Jin[3*]

Abstract

Background The Healthy Eating Index (HEI-2015) assesses dietary quality, and lower scores may be associated with an increased risk of frailty. However, few epidemiological studies have examined the relationship between HEI-2015 and the Frailty Index (FI). This study explores the association between HEI-2015 and FI using data from the U.S. National Health and Nutrition Examination Survey (NHANES), analyzing how factors such as gender and age influence this relationship.

Methods TNHANES data (2007–2018) were analyzed using logistic regression models to assess the HEI-2015-frailty association. Frailty diagnosis was based on physical activity, strength, fatigue, weight change, and gait speed, with FI scores ranging from 0 to 1. A threshold of 0.21 classified frailty. The R package "DALEX" was used for feature importance analysis to enhance the prediction of frailty. From this analysis, we selected 10 key factors to further improve the accuracy of frailty prediction.

Result Of 14,300 participants, 16.2% (2,322) were classified as frail. Frail participants had lower income, higher BMI, lower physical activity, and lower HEI-2015 scores. Higher HEI-2015 scores were associated with reduced frailty risk (adjusted OR: 0.69, 95% CI: 0.56–0.87, $P<0.01$). The negative association was stronger in women, higher-income groups, and those with higher education ($P<0.01$). Feature importance analysis showed HEI-2015 was the top predictor of frailty.

Conclusion Higher HEI-2015 scores are linked to lower frailty risk. Promoting healthy eating may prevent frailty, especially in high-risk groups, with education and demographic factors influencing this relationship.

Keywords NHANES, Hei, Frailty

Introduction

The Healthy Eating Index (HEI) is a widely used tool to quantitatively evaluate dietary patterns and quality [1]. The 2015 version of the Healthy Eating Index (HEI-2015) was developed based on the 2015–2020 Dietary Guidelines for Americans (DGA)2 to provide a comprehensive measure of diet quality. Previous studies have shown that healthy eating is associated with increased life expectancy and a reduced risk of adverse health outcomes. Higher HEI-2015 scores indicate better dietary quality and are positively correlated with improved mental health [2–4].However, these studies often fail to fully

[†]Ting He contributed equally to the writing of this article.

*Correspondence:
Tingting Peng
2397631564@qq.com
Liuyin Jin
2407581536@qq.com
[1]Shaoxing Seventh People's Hospital (Affiliated Mental Health Center, Medical College of Shaoxing University）, Shaoxing, China
[2]The First Clinical Medical College, Guangdong Medical University, Zhanjiang, China
[3]The Second People's Hospital of Lishui, Lishui, China
[4]Peking University Medical Zibo Hospital, Zibo, China

elucidate the impact of poor dietary quality on the risk of specific diseases or its underlying mechanisms. While a healthy diet is recognized as an essential strategy for improving health, the precise pathways through which it exerts its effects remain unclear [5, 6].

The Frailty Index (FI) is a quantitative tool that assesses an individual's vulnerability by accumulating various health deficits. FI reflects overall health frailty and can predict aging-related health risks, including disease prevalence and mortality [7–10]. The relationship between dietary quality and frailty may arise from the critical role of nutrition in maintaining bodily functions. High-quality diets provide essential micronutrients and antioxidants, reducing chronic inflammation and oxidative stress, thereby preserving muscle mass, bone health, and immune function, ultimately lowering the risk of frailty. The relationship between dietary quality and frailty may stem from the critical role of nutrition, including both micronutrients and macronutrients, in maintaining bodily functions [11]. Excessive intake of certain macronutrients, however, could negatively impact health and increase frailty risk [12]. High-quality diets provide essential micronutrients and antioxidants, reducing chronic inflammation and oxidative stress, thereby preserving muscle mass, bone health, and immune function, ultimately lowering the risk of frailty [13–18].Although several studies have investigated the relationship between diet and frailty, including research utilizing NHANES data, they have not systematically analyzed the association between HEI-2015 and FI [19].Therefore, this study aims to address this gap in the literature by analyzing NHANES data from 2007 to 2018. Specifically, the objectives are to: (1) examine the relationship between HEI-2015 scores and FI and (2) identify and evaluate factors such as diet, physical activity, BMI, and socioeconomic status that influence frailty risk using multivariate models and feature importance analysis.

Method

Study design and participants

The participants who engaged in the National Health and Nutrition Examination Survey (NHANES) cycles from 2007 to 2018. The final analytic sample size of adults (age ≥ 20) with no missing data for any variables is $N = 14{,}300$. Additional details of the study design, sampling, and exclusion criteria are illustrated in Fig. 1.

NHANES is a nationally representative, population-based survey for assessing the health and nutritional status of adults and children in the United States. This survey examines a nationally representative sample of about 5,000 persons each year. It is noteworthy that NHANES over-samples persons 60 and older, African Americans and Hispanics, to produce reliable statistics. Other population details, recruitment, characteristics, and procedures for NHANES are provided through the Centers for Disease Control and Prevention [20] (https://www.cdc.gov/nchs/nhanes/index.htm). Only publicly available data was used in the analysis, and no ethical approval was needed in this study.

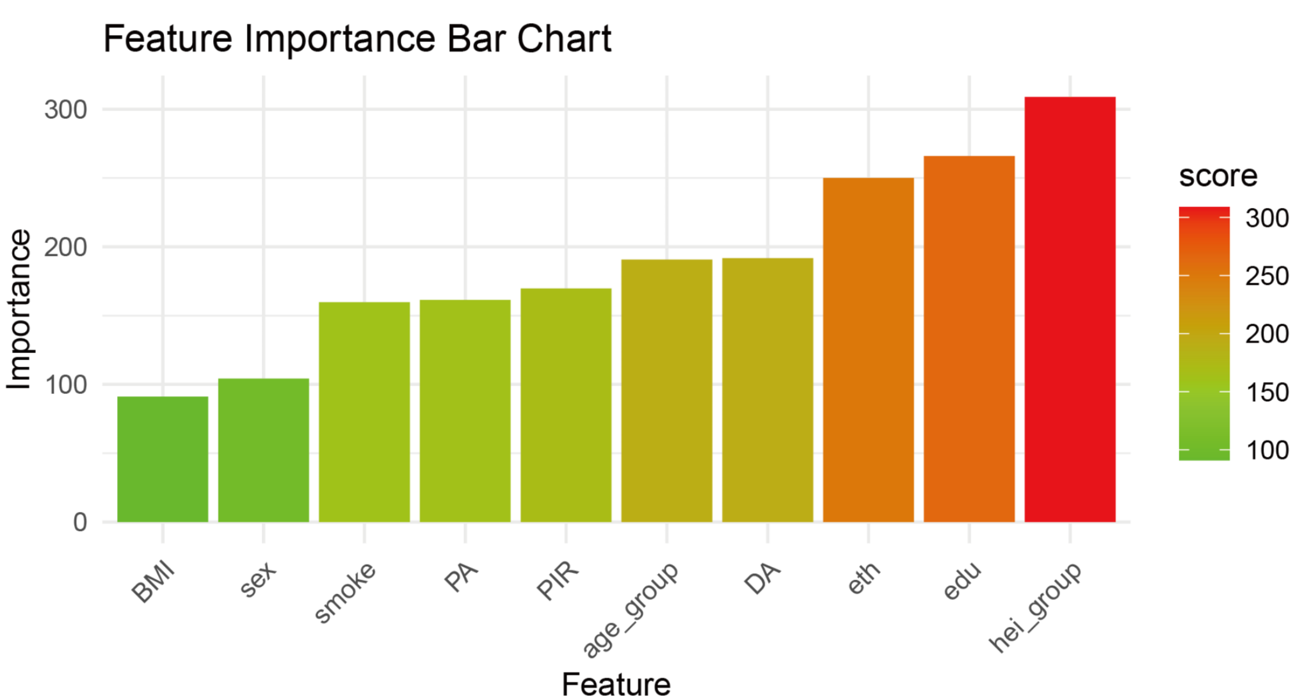

Fig. 1 The flow diagram of screening participants from NHANES

Measures

Healthy eating index 2015

hei-2015 was an indicator for assessing dietary quality [21], namely the degree to which a set of nutrients is consistent with the Dietary Guidelines for Americans [22] (DGA). This eating behavior evaluation questionnaire comprised 13 kinds of components to assess the degree of adherence to DGA. These components were marshaled into two forms of diet lists, which included the adequacy components (total fruits, total vegetables, total protein foods, greens and beans, whole fruits, seafood, plant proteins, whole grains, dairy, fatty acids) and the moderation components (added sugars, sodium, saturated fats, refined grains) [4]. Higher intakes will be scored more by hei-2015 for the group of adequacy components. However, higher scores reflected lower moderation component intakes for the group of moderation components. With the combination of two groups together, the hei-2015 component and total scores were calculated by the hei scoring algorithm using the R software.

Previous studies had assessed the hei-2015 of reliability, internal consistency, and construct validity [23, 24]. In our study, dietary information was extracted from data collected by a professional interviewer face-to-face in the MEC for a 24-hour dietary recall.

The hei-2015 scored out of 100 points. The total hei-2015 scores were calculated using the mean value of nutrient intakes between the first-day intakes (DR1TOT) and the second-day intakes (DR2TOT).

Frailty

A frailty index was applied to count deficits in health. These deficits were defined as diseases, disabilities, signs, and symptoms [25]. The understanding that the frailty index as an independent predictor mattered concerning determining a piece of health-state information from several physiological systems was strongly associated with lower hei-2015 scores in frailty populations.

According to the standard procedure introduced by Searle's study [26] and the further study of Hakeem and colleagues [27], the frailty index included 49 deficits that covered cognition, dependence, depressive symptoms, comorbidities, hospital utilization and access to care, physical performance and anthropometry, and laboratory values.

Frailty index scores ranged from 0 (indicating no health deficits) to 1 (indicating every health deficit assessed). Based on proposed cutoff scores usually used in epidemiological studies, we put to use a frailty index cutoff that was classified as "non-frail" (FI $\leq$ 0.21) or frail (FI $>$ 0.21) to obtain greater accuracy for the definition of frailty [28]. Information regarding the 49 deficits included in the Frailty Index can be found in the supplementary.docx.

Covariates and definitions

The following covariates were obtained from questionnaires conducted by professional interviewer: age group (>= 60 years, 20 ~ 39 years, 40 ~ 59 years), gender, education (< 9 grade, 9-11th Grade, College, GED, Some College), ethnicity (Mexican American, Non-Hispanic Black, Non-Hispanic White, Other Race), body mass index (BMI: high, low, normal), poverty-to-income ratio (PIR), drink alcohol (DA), In this study, physical activity (PA) data were obtained through the NHANES survey questionnaire, which covers various types of activities, including work, household chores, and leisure-time activities. PA was categorized into three levels—low, moderate, and high—based on activity intensity and duration. Low-intensity activities include walking or light household chores, moderate-intensity activities encompass brisk walking or gardening, and high-intensity activities involve vigorous exercises such as running or fitness workouts [29].Smoking status was defined as follows: never (smoked less than 100 cigarettes in life), former (smoked more than 100 cigarettes in life and smoke not at all now), now (smoked more than 100 cigarettes in life and smoke some days or every day).

Statistical analysis

Continuous variables were presented as mean and standard deviation, and categorical variables were presented as numbers or percentages. We assessed the distribution of hei-2015 and relevant covariates. Quintiles of reliability-adjusted hei-2015 scores were recorded and calculated into five contiguous groups respectively, with each group representing approximately 20% of the sample population, ensuring equal representation across the hei-2015 spectrum. Differences in hei groups, characteristics, and other parameters between the five groups of hei-2015 scores were tested using the weighted Wilcoxon rank sum test for continuous variables or the weighted Pearson's Chi-squared test for categorical variables where appropriate.

All analyses used the NHANES sampling weights, and the complex multistage cluster survey design of NHANES was taken into account. A value of $p < 0.05$ was used as a cutoff to demonstrate statistical significance. This study applied multivariate logistic regression to assess the associations of hei groups with frailty and calculated odds ratios (OR) with 95% confidence intervals (CI) for frailty risk (FI $>$ 0.21 was regarded as frailty). Then, several adjusted models were conducted: model 1 (without any adjustments for covariates), model 2 (adjusted for age, race, education level, PIR, and BMI on top of Model 1), and model 3 (building on Model 2, further incorporated smoking, physical activity, and alcohol consumption).

In addition, we used the "DALEX" package in R version 4.3.2 to improve the interpretability of the final model [30]. This visualization method was used to calculate feature importance and show clinical variables in terms of importance. The "model_parts" command of DALEX package [30] allowed us to understand the relationship between the variables and the clinical outcomes and assess each variable's contribution to individual predictions [31–34].

Results

Population characteristics

Table 1 presents the sample number and weighted percentages with significance levels for differences within variable categories. A total of 14,300 participants were covered, which were predominantly Non-Hispanic White, with approximately 19.7% Non-Hispanic Black, 13.7% Mexican American, and 19.9% other. It represented approximately 3,000 million inhabitants of the United States. At baseline, 2,322 participants (16.2%) met the frailty by frailty index criteria. Notably, significant

Table 1 Participants in the cohort according to the characteristics of the frailty State

Variable	*N*	0, *N* = 11,978	1, *N* = 2,322	*p*-value	q-value[1]
gender, n (%)	14,300			< 0.001[2]	< 0.001
Female		5,162 (43)	1,227 (53)		
Male		6,816 (57)	1,095 (47)		
ethnicity, n (%)	14,300			< 0.001[2]	< 0.001
Mexican American		1,698 (14)	264 (11)		
Non-Hispanic Black		2,211 (18)	620 (27)		
Non-Hispanic White		5,614 (47)	1,040 (45)		
Other Race		2,455 (20)	398 (17)		
education, n (%)	14,300			< 0.001[2]	< 0.001
< 9 grade		544 (4.5)	180 (7.8)		
9-11th Grade		1,284 (11)	362 (16)		
College		3,692 (31)	399 (17)		
GED		2,462 (21)	581 (25)		
Some College		3,996 (33)	800 (34)		
smoke, n (%)	14,300			< 0.001[2]	< 0.001
former		2,750 (23)	694 (30)		
never		6,616 (55)	889 (38)		
now		2,612 (22)	739 (32)		
total hei-2015 score, Median (IQR)	14,300	50.640 (41.219–60.959)	48.385 (39.025–58.227)	< 0.001[3]	< 0.001
age_group, n (%)	13,991			< 0.001[2]	< 0.001
>=60 years		2,546 (22)	770 (34)		
20 ~ 39 years		5,450 (46)	477 (21)		
40 ~ 59 years		3,740 (32)	1,008 (45)		
body mass index, n (%)	14,300			< 0.001[2]	< 0.001
high		7,934 (66)	1,871 (81)		
low		179 (1.5)	29 (1.2)		
Normal		3,865 (32)	422 (18)		
poverty-to-income ratio, n (%)	14,300			< 0.001[2]	< 0.001
high income		4,678 (39)	561 (24)		
low income		2,955 (25)	915 (39)		
middle income		4,345 (36)	846 (36)		
hei_group, n (%)	14,300			< 0.001[2]	< 0.001
1		2,304 (19)	556 (24)		
2		2,356 (20)	504 (22)		
3		2,421 (20)	439 (19)		
4		2,401 (20)	459 (20)		
5		2,496 (21)	364 (16)		

Notefoot: 0 indicates a diagnosis of no frailty, 1 indicates a diagnosis of frailty

[1]False discovery rate correction for multiple testing

[2]Pearson's Chi-squared test

[3]Wilcoxon rank sum test

differences were observed in demographic and baseline clinical characteristics between participants diagnosed with frailty (Frailty Index > 0.21 was regarded as frailty) and those without frailty. Participants with frailty tended to have lower income (915 (39.4%) vs. 2,955 (24.6%)), higher BMI (1,871(80.5%) vs. 7,934 (66.2%)), lower exercise (548 (23.6%) vs. 1,778 (14.8%)), lower total hei-2015 scores (48.385 (39.025–58.227) vs. 50.640 (41.219–60.959)) and higher waistline measurements (102.19 (17.66) vs. 99.19 (16.03)). It is evident that older adults (≥ 60 years) are much more likely to report frailty. Additionally, smoking status appeared to influence the occurrence of frailty.

A higher healthy eating index score is associated with a lower risk of frailty

In the correlation analysis, multivariate logistic regression results for frailty show that higher HEI-2015 quintiles are significantly associated with lower odds of frailty across all models.In the unadjusted model (Model 1), compared to the reference group (Q1), the odds ratios (OR) for frailty decreased across higher quintiles: Q2 (OR: 0.77, 95% CI: 0.64–0.93, $P = 0.01$), Q3 (OR: 0.71, 95% CI: 0.59–0.85, $P < 0.001$), Q4 (OR: 0.78, 95% CI: 0.65–0.92, $P = 0.005$), and Q5 (OR: 0.58, 95% CI: 0.48–0.70, $P < 0.0001$).In the minimally adjusted model (Model 2), adjusting for age, race, education, PIR, and BMI, the ORs remained similar: Q2 (OR: 0.73, 95% CI: 0.59–0.91, $P = 0.01$), Q3 (OR: 0.71, 95% CI: 0.57–0.89, $P = 0.003$), Q4 (OR: 0.78, 95% CI: 0.63–0.95, $P = 0.02$), and Q5 (OR: 0.65, 95% CI: 0.52–0.81, $P < 0.001$).In the fully adjusted model (Model 3), with additional adjustments for physical activity (PA), smoking status, and alcohol consumption (DA), the pattern remained robust: Q2 (OR: 0.74, 95% CI: 0.60–0.91, $P = 0.01$), Q3 (OR: 0.72, 95% CI: 0.58–0.90, $P = 0.005$), Q4 (OR: 0.81, 95% CI: 0.66–0.99, $P = 0.04$), and Q5 (OR: 0.69, 95% CI: 0.56–0.87, $P = 0.002$),more information can be found in Table 2.

Stratified associations between frailty and hei-2015 scores

As shown in Table 3, we conducted further stratified analysis on the following covariates, including: age group, gender, education, ethnicity, BMI, family income to PIR, smoking, PA, DA to assess the associations between hei-2015 and frailty. Likely, healthy eating index levels of females, high income, non-Hispanic white, alcohol middle intake, 40 ~ 59 years, higher BMI, and college were significantly positively correlated with frailty. (p for trend < 0.0001; p for trend < 0.001; p for trend < 0.001; p for trend < 0.0001; p for trend < 0.0001; p for trend = 0.002; p for trend = 0.035). In addition, we detected variables of education and hei-2015 scores may have an interaction effect associated with frailty risk (p for interaction = 0.004).

Feature importance

Figure 2 shows the level of importance features have in a local environment to quantify relative importance (both positive and negative) of selected clinical variables associated with the frailty on the model. We chose a total of 10 clinical variables in terms of importance in Fig. 2 and calculated feature importance as a score using the "DALEX" package [30, 32, 35]. Based on the condition of the feature importance analysis, The hei_group (diet quality score) is the most important feature, playing a crucial role in predicting frailty, with an importance score close to 300. Following this are edu (education level) and eth (ethnicity), both with high importance scores exceeding 250. Other features, such as DA (disease burden), age_group (age group), PIR (poverty income ratio), and PA (physical activity), show moderate importance, with scores around 200. In contrast, smoke (smoking status), sex (gender), and BMI (body mass index) still hold some importance but with lower scores ranging from approximately 100 to 150.

Discussion

Recently, the discovery of the frailty index related to nutrition [36, 37], physical activity [38], age [39], and age-related diseases [40–43] has sparked significant interest in the scientific community, leading to extensive research on frailty and its implications [40, 44]. The decline across these multiple physiological systems triggers increased utilization of medical and social resources with consequent economic expenditures [19].

While the medical and socio-economic issues associated with frailty are deeply rooted, there is nonetheless encouraging evidence to suggest that dietary

Table 2 P value of frailty prevalence according to hei-2015 in the NHANSE

hei-2015	Model 1		Model 2		Model 3	
character	OR(95%CI)	P	OR(95%CI)	P	OR(95%CI)	P
Q1	ref		ref		ref	
Q2	0.77(0.64,0.93)	0.01	0.73(0.59,0.91)	0.01	0.74(0.60,0.91)	0.01
Q3	0.71(0.59,0.85)	< 0.001	0.71(0.57,0.89)	0.003	0.72(0.58,0.90)	0.005
Q4	0.78(0.65,0.92)	0.005	0.78(0.63,0.95)	0.02	0.81(0.66,0.99)	0.04
Q5	0.58(0.48,0.70)	< 0.0001	0.65(0.52,0.81)	< 0.001	0.69(0.56,0.87)	0.002
p for trend(character2integer)		< 0.0001		0.002		0.01

Table 3 Stratified association between frailty prevalence and hei-2015 in the NHANSE

Variable	Q1	Q2	*p*	Q3	*p*	Q4	*p*	Q5	*p*	*p* for trend(character2integer)	*p* for interaction
gender											0.018
Female	ref	0.756(0.585,0.977)	**0.033**	0.568(0.437,0.738)	**< 0.0001**	0.616(0.494,0.769)	**< 0.0001**	0.444(0.347,0.567)	**< 0.0001**	**< 0.0001**	
Male	ref	0.774(0.574,1.044)	0.092	0.855(0.674,1.084)	0.194	0.935(0.709,1.232)	0.628	0.720(0.547,0.947)	**0.019**	0.11	
poverty-to-income ratio											0.234
middle income	ref	0.893(0.668,1.193)	0.44	0.959(0.711,1.293)	0.781	0.984(0.728,1.330)	0.915	0.875(0.644,1.188)	0.388	0.612	
high income	ref	0.656(0.438,0.983)	**0.041**	0.576(0.388,0.856)	**0.007**	0.628(0.446,0.882)	**0.008**	0.517(0.361,0.739)	**< 0.001**	**< 0.001**	
low income	ref	0.879(0.685,1.127)	0.305	0.780(0.582,1.046)	0.096	1.036(0.780,1.376)	0.805	0.733(0.515,1.043)	0.084	0.288	
ethnicity											0.091
Mexican American	ref	1.253(0.738,2.127)	0.398	0.842(0.461,1.539)	0.572	1.177(0.781,1.774)	0.429	0.835(0.506,1.381)	0.478	0.431	
Non-Hispanic Black	ref	1.043(0.777,1.401)	0.776	0.816(0.591,1.126)	0.213	0.896(0.655,1.226)	0.489	0.845(0.620,1.152)	0.283	0.155	
Non-Hispanic White	ref	0.712(0.548,0.925)	**0.012**	0.744(0.576,0.963)	**0.025**	0.784(0.617,0.997)	**0.047**	0.563(0.430,0.737)	**< 0.0001**	**< 0.001**	
Other Race	ref	0.618(0.393,0.971)	**0.037**	0.394(0.250,0.619)	**< 0.0001**	0.541(0.355,0.825)	**0.005**	0.478(0.287,0.797)	**0.005**	**0.006**	
drink alcohol											0.016
high intake	ref	0.777(0.546,1.106)	0.158	0.671(0.469,0.959)	**0.029**	0.887(0.627,1.256)	0.497	0.517(0.312,0.860)	**0.012**	**0.02**	
light intake	ref	0.845(0.632,1.130)	0.252	0.904(0.690,1.185)	0.462	0.995(0.770,1.286)	0.971	0.674(0.518,0.877)	**0.004**	**0.02**	
Middle intake	ref	0.671(0.465,0.968)	**0.033**	0.461(0.321,0.662)	**< 0.0001**	0.406(0.279,0.592)	**< 0.0001**	0.482(0.323,0.719)	**< 0.001**	**< 0.0001**	
age_group											0.208
40 ~ 59 years	ref	0.593(0.433,0.813)	**0.001**	0.513(0.382,0.689)	**< 0.0001**	0.567(0.418,0.771)	**< 0.001**	0.387(0.285,0.526)	**< 0.0001**	**< 0.0001**	
20 ~ 39 years	ref	0.819(0.599,1.121)	0.21	0.679(0.519,0.889)	**0.005**	0.564(0.408,0.781)	**< 0.001**	0.381(0.226,0.643)	**< 0.001**	**< 0.0001**	
>=60 years	ref	0.750(0.498,1.131)	0.168	0.830(0.527,1.306)	0.416	0.860(0.591,1.251)	0.426	0.655(0.452,0.949)	**0.026**	0.096	
body mass index											0.163
high	ref	0.850(0.677,1.066)	0.157	0.779(0.633,0.959)	**0.019**	0.855(0.702,1.042)	0.118	0.707(0.577,0.867)	**0.001**	**0.002**	
Normal	ref	0.633(0.420,0.954)	**0.029**	0.572(0.362,0.903)	**0.017**	0.625(0.400,0.977)	**0.04**	0.451(0.287,0.711)	**< 0.001**	**0.002**	
low	ref	0.192(0.041,0.891)	**0.036**	0.061(0.011,0.342)	**0.002**	0.461(0.092,2.306)	0.335	0.143(0.032,0.629)	**0.012**	0.126	
education											0.004
< 9 grade	ref	1.543(0.862,2.763)	0.142	1.061(0.520,2.166)	0.869	1.005(0.515,1.962)	0.988	0.551(0.287,1.056)	0.072	0.053	
GED	ref	0.611(0.435,0.860)	**0.005**	0.647(0.434,0.964)	**0.033**	1.124(0.848,1.491)	0.412	0.925(0.607,1.411)	0.716	0.599	
9-11th Grade	ref	0.774(0.533,1.124)	0.176	0.529(0.344,0.815)	**0.004**	0.939(0.615,1.434)	0.768	0.710(0.425,1.187)	0.189	0.226	
College	ref	0.456(0.280,0.745)	**0.002**	0.643(0.397,1.042)	0.073	0.568(0.347,0.930)	**0.025**	0.545(0.368,0.807)	**0.003**	**0.035**	
Some College	ref	1.163(0.858,1.577)	0.327	0.982(0.741,1.301)	0.897	0.991(0.723,1.357)	0.952	0.786(0.594,1.041)	0.092	0.065	

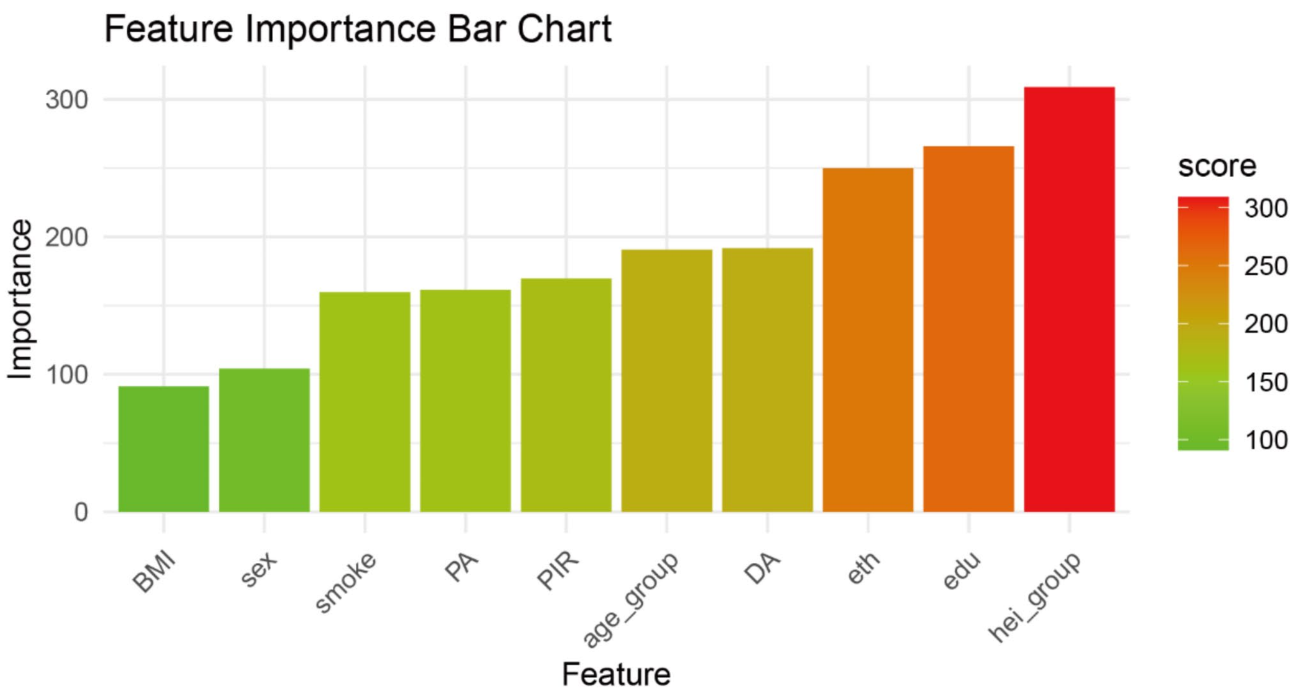

Fig. 2 The level of importance feature, BMI: body mass index; PA: physical activity; PIR: poverty-to-income ratio; DA: drink alcohol; eth: ethnicity; edu: education

interventions can improve the occurrence of frailty. Micronutrients, including lycopene [45], vitamin E [46–48], and vitamin D [49], have been shown to intervene in the occurrence of frailty. Therefore, an adequate intake of foods rich in proteins, lycopene, vitamin E, and vitamin D may help delay the onset of frailty. Additionally, based on both previous studies and findings from our research team, vegetables and fruits have been shown to have a similar effect in preventing frailty in the elderly population [50–53]. However, the above-mentioned studies only focused on a specific nutrient or a particular food, and the HEI-2015 index has not yet been used to evaluate the relationship between dietary intake quality and the risk of frailty. Therefore, we conducted this study. Our study results indicate a significant association between HEI-2015 and the risk of frailty, with higher HEI scores correlating to a lower risk of frailty. In multivariate regression analysis across different models, both unadjusted and adjusted models consistently showed that higher HEI scores were significantly associated with reduced frailty risk. Numerous studies have demonstrated that high-quality dietary patterns, such as the Mediterranean diet or diets with higher HEI scores, can significantly reduce the risk of frailty [54–56]. Some research even suggests that high-quality diets may reverse frailty. Our findings further support these observations, emphasizing the importance of dietary quality, particularly the HEI-2015 score, in predicting frailty.In our stratified analysis, we examined the impact of various covariates on the relationship between the HEI score and frailty. The results showed that the effect of the HEI score on frailty risk was more pronounced in certain subgroups, including females, high-income individuals, non-Hispanic Whites, those aged 40–59 years, and those with high BMI.First, gender differences may play a significant role in the relationship between dietary quality and frailty. Compared to men, women have different nutritional needs, metabolic rates, and hormonal levels, which could lead to a greater reduction in frailty risk when dietary quality improves [57]. For example, studies have shown that postmenopausal women face a higher risk of frailty due to declining estrogen levels and may rely more on dietary antioxidants to mitigate frailty. Second, racial and ethnic differences may influence the relationship between dietary quality and frailty through factors such as socioeconomic status, cultural background, and dietary habits [58]. Minority groups, particularly those facing long-term social and economic inequality, may experience heightened effects of dietary quality on health outcomes due to chronic stress and adverse health conditions [59]. Additionally, culturally influenced dietary habits could impact health outcomes. For instance, some studies suggest that traditional diets rich in fiber and plant-based foods among non-White populations may contribute to the protective effect of healthy diets on frailty.Finally, alcohol consumption may also be an important factor. Several studies have shown that moderate alcohol intake is associated with a reduced risk of cardiovascular disease, which could indirectly affect the development of frailty [60]. Moderate drinkers are often more likely to engage in other health-promoting behaviors, such as balanced eating and regular exercise, which together may help prevent frailty.

From the feature importance analysis, hei_group emerged as the most crucial predictor of frailty, with a score close to 300. Education and ethnicity followed closely with scores exceeding 250, indicating the significant impact of socioeconomic and demographic factors on frailty risk. Additionally, factors such as DA, age group, PIR, and PA had moderate importance scores around 200. In contrast, smoke, gender (sex), and BMI had lower importance scores, ranging between 100 and 150.These findings highlight the strong relationship between healthy diets and frailty, suggesting that dietary quality is a powerful predictor of frailty. However, various factors may contribute to declines in HEI scores, including unhealthy lifestyle behaviors and pathological conditions. For example, in older adults, a decline in dietary quality may be closely linked to tooth loss. Research by Xu Kehui et al. found that as the number of lost teeth increased, dietary quality decreased and was negatively associated with accelerated aging. Mediation analysis revealed that HEI scores partially mediated the relationship between tooth loss and accelerated aging (mediation proportion: 5.302%; 95% CI: 3.422–7.182%; $P < 0.001$) [61, 62].Our study highlights the close relationship between health factors and frailty, indicating that promoting healthy diets can effectively reduce the incidence of frailty, particularly in older adults. Therefore, future research should further explore factors contributing to declines in HEI scores. Early intervention in populations at risk of poor dietary quality may help slow or prevent the progression of frailty, thereby improving patients' quality of life.

Although this cross-sectional study provides valuable preliminary insights into the relationship between dietary quality and frailty, it has several limitations. Cross-sectional designs capture associations at a single point in time, making it impossible to establish causality. This means that we cannot determine whether dietary quality influences frailty or if frailty leads to a decline in dietary quality. Additionally, the possibility of reverse causation cannot be ignored, as frail individuals may choose poor diets due to physical limitations, complicating the interpretation of the associations further.Confounding factors are another crucial consideration. Despite efforts to control for known confounders, unmeasured factors may still bias the results. Self-reported dietary data may also be subject to recall bias or social desirability bias, affecting the accuracy of the findings. Sample selection bias may also occur, especially in studies targeting specific populations (e.g., older adults or patients with chronic illnesses), which can limit the generalizability of the results. Furthermore, variations in dietary quality assessment methods across studies, such as the use of different dietary tools (e.g., food frequency questionnaires or 24-hour dietary recalls), may affect the consistency and comparability of findings.Dietary assessment tools are also associated with under and overestimation of intake.The lack of bivariate analysis is another limitation, as it restricts the exploration of key variable relationships. Bivariate analysis can help identify which variables have significant associations with frailty and detect potential interactions between variables, thereby guiding subsequent multivariable models. However, many cross-sectional studies do not systematically perform such analyses, which may result in the omission of important potential variables.Despite these limitations, the findings provide valuable insights into the relationship between dietary quality and frailty, though they should be interpreted with caution. Future longitudinal research is recommended to explore the causal relationship between dietary quality and frailty more comprehensively.Several approaches can help overcome the limitations of cross-sectional data in future research, allowing for a more in-depth exploration of the causal relationship between dietary quality and frailty. First, adopting longitudinal study designs is essential, as they track changes in individuals' dietary habits and frailty status over time, offering a clearer understanding of how dietary quality influences the onset and progression of frailty. Second, randomized controlled trials (RCTs) can be introduced to directly observe the impact of dietary interventions on frailty, providing stronger evidence. Additionally, advanced statistical methods, such as structural equation modeling (SEM) or causal inference models (e.g., instrumental variable methods), can help researchers better address causality and reduce the influence of confounders.To address sample representativeness and measurement differences, future research should aim to use large, diverse population samples and standardize dietary assessment tools across multiple centers to enhance the generalizability and credibility of findings. Bivariate analysis should also be incorporated in the early stages of data processing to identify key variables that significantly impact frailty and provide a solid foundation for multivariable modeling. Integrating data from multiple sources, including biomarkers, imaging data, and objective measures of physical activity, can further improve analysis accuracy and reduce biases related to self-reported data. Lastly, strengthening the control of confounders during data collection, such as detailed recording of socioeconomic status, mental health, and other relevant variables, can help minimize bias and enhance the reliability of results. These approaches will enable future research to more accurately uncover the complex relationship between dietary quality and frailty.

Conclusions

This study demonstrates a significant association between the Healthy Eating Index (HEI-2015) and the risk of frailty, with higher HEI scores linked to a lower risk of frailty. Multivariate regression and stratified analyses support the protective role of high-quality dietary patterns, such as the Mediterranean diet, in preventing or even reversing frailty, particularly among females, high-income groups, non-Hispanic Whites, those aged 40–59 years, and individuals with high BMI.Feature importance analysis highlights dietary quality as a key predictor of frailty, with education and ethnicity also showing significant influence. Declines in HEI scores may result from unhealthy lifestyles or pathological factors, such as the relationship between tooth loss and accelerated aging. Promoting healthy diets can effectively reduce the incidence of frailty, improve quality of life for older adults, and alleviate healthcare burdens. However, this cross-sectional study cannot establish causation, and potential reverse causation and unmeasured confounders may affect the results. Therefore, future research should adopt longitudinal designs and randomized controlled trials (RCTs) to further explore the long-term effects of dietary quality on frailty.We recommend that future studies use large, diverse samples, standardize dietary assessment tools, and incorporate bivariate analysis and multi-source data integration to improve the accuracy, generalizability, and reliability of the findings.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22245-x.

Supplementary Material 1

Author contributions

T.H. made the greatest contribution to this study. Y.f. Y. and D.D. W. did the Bibliometrics analysis and wrote the manuscript. L.y. J. and T.t. P. supervised and revised the manuscript. All authors contributed to the article and approved the submitted version.

Funding

There has been no funding received for this study.

Data availability

Dataset can be found at NHANES online website: https://www.cdc.gov/nchs/nhanes/index.htm.

Declarations

Ethical approval and participant consent

The studies involving humans were approved by The NHANES study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of the institutional review board of the National Center for Health Statistics, CDC (protocol #2005–06, #2011–17, #2018–01). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 21 September 2024 / Accepted: 7 March 2025
Published online: 19 March 2025

References

1. Zhuang Y, Krumm B, Zhang H, Zhou XE, Wang Y, Huang XP, Liu Y, Cheng X, Jiang Y, Jiang H, et al. Mechanism of dopamine binding and allosteric modulation of the human D1 dopamine receptor. Cell Res. 2021;31(5):593–6.
2. Ocké MC. Evaluation of methodologies for assessing the overall diet: dietary quality scores and dietary pattern analysis. Proc Nutr Soc. 2013;72(2):191–9.
3. Liese AD, Krebs-Smith SM, Subar AF, George SM, Harmon BE, Neuhouser ML, Boushey CJ, Schap TE, Reedy J. The dietary patterns methods project: synthesis of findings across cohorts and relevance to dietary guidance. J Nutr. 2015;145(3):393–402.
4. Krebs-Smith SM, Pannucci TE, Subar AF, Kirkpatrick SI, Lerman JL, Tooze JA, Wilson MM, Reedy J. Update of the healthy eating index: HEI-2015. J Acad Nutr Dietetics. 2018;118(9):1591–602.
5. Kim MJ, Park JE, Park JH. Associations of healthy eating behavior with mental health and health-Related quality of life: results from the Korean National representative survey. Nutrients 2023, 15(24).
6. Martínez-González MA, Sánchez-Villegas A. Food patterns and the prevention of depression. *The Proceedings of the Nutrition Society* 2016, 75(2):139–146.
7. Khaled K, Tsofliou F, Hundley V, Helmreich R, Almilaji O. Perceived stress and diet quality in women of reproductive age: a systematic review and meta-analysis. Nutr J. 2020;19(1):92.
8. Molendijk M, Molero P, Ortuño Sánchez-Pedreño F, Van der Does W, Angel Martínez-González M. Diet quality and depression risk: A systematic review and dose-response meta-analysis of prospective studies. J Affect Disord. 2018;226:346–54.
9. Jansen EC, Prather A, Leung CW. Associations between sleep duration and dietary quality: results from a nationally-representative survey of US adults. Appetite. 2020;153:104748.
10. Shan Z, Wang F, Li Y, Baden MY, Bhupathiraju SN, Wang DD, Sun Q, Rexrode KM, Rimm EB, Qi L, et al. Healthy eating patterns and risk of total and Cause-Specific mortality. JAMA Intern Med. 2023;183(2):142–53.
11. Ni Lochlainn M, Cox NJ, Wilson T, Hayhoe RPG, Ramsay SE, Granic A, Isanejad M, Roberts HC, Wilson D, Welch C et al. Nutrition and frailty: opportunities for prevention and treatment. Nutrients 2021, 13(7).
12. Zhang K, Wu J. Meat-Egg-Dairy consumption and frailty among Chinese older adults: exploring rural/urban and gender differences. Nutrients 2024, 16(9).
13. Atkins JL, Jylhävä J, Pedersen NL, Magnusson PK, Lu Y, Wang Y, Hägg S, Melzer D, Williams DM, Pilling LC. A genome-wide association study of the frailty index highlights brain pathways in ageing. Aging Cell. 2021;20(9):e13459.
14. Kojima G, Iliffe S, Walters K. Frailty index as a predictor of mortality: a systematic review and meta-analysis. Age Ageing. 2018;47(2):193–200.
15. Xu Q, Jia Y, Wang Y, Yang P, Sun L, Liu Y, Chang X, He Y, Guo D, Shi M, et al. The bidirectional association between frailty index and cardiovascular disease: A Mendelian randomization study. Nutr Metabolism Cardiovasc Diseases: NMCD. 2024;34(3):624–32.
16. Zhang J, Wang Q, Hao W, Zhu D. Long-Term food variety and dietary patterns are associated with frailty among Chinese older adults: A cohort study based on CLHLS from 2014 to 2018. Nutrients 2022, 14(20).
17. Vicente BM, Lucio Dos Santos Quaresma MV, Maria de Melo C, Lima Ribeiro SM. The dietary inflammatory index (DII®) and its association with cognition, frailty, and risk of disabilities in older adults: A systematic review. Clin Nutr ESPEN. 2020;40:7–16.
18. Blodgett JM, Theou O, Howlett SE, Rockwood K. A frailty index from common clinical and laboratory tests predicts increased risk of death across the life course. GeroScience. 2017;39(4):447–55.
19. Lorenzo-López L, Maseda A, de Labra C, Regueiro-Folgueira L, Rodríguez-Villamil JL, Millán-Calenti JC. Nutritional determinants of frailty in older adults: A systematic review. BMC Geriatr. 2017;17(1):108.

20. National Center for Health Statistics. National Health and Nutrition Examination Survey. Atlanta: Centers for Disease Control and Prevention. 2018. [cited 2018 Nov 29]. Available from: https://www.cdc.gov/nchs/nhanes/index.htm
21. Reedy J, Lerman JL, Krebs-Smith SM, Kirkpatrick SI, Pannucci TE, Wilson MM, Subar AF, Kahle LL, Tooze JA. Evaluation of the healthy eating Index-2015. J Acad Nutr Dietetics. 2018;118(9):1622–33.
22. DeSalvo KB, Olson R, Casavale KO. Dietary guidelines for Americans. JAMA. 2016;315(5):457–8.
23. Kirkpatrick SI, Reedy J, Krebs-Smith SM, Pannucci TE, Subar AF, Wilson MM, Lerman JL, Tooze JA. Applications of the healthy eating index for surveillance, epidemiology, and intervention research: considerations and caveats. J Acad Nutr Dietetics. 2018;118(9):1603–21.
24. Panizza CE, Shvetsov YB, Harmon BE, Wilkens LR, Le Marchand L, Haiman C, Reedy J, Boushey CJ. Testing the Predictive Validity of the Healthy Eating Index-2015 in the Multiethnic Cohort: Is the Score Associated with a Reduced Risk of All-Cause and Cause-Specific Mortality? *Nutrients* 2018, 10(4).
25. Rockwood K, Mitnitski A. Frailty in relation to the accumulation of deficits. Journals Gerontol Ser Biol Sci Med Sci. 2007;62(7):722–7.
26. Searle SD, Mitnitski A, Gahbauer EA, Gill TM, Rockwood K. A standard procedure for creating a frailty index. BMC Geriatr. 2008;8:24.
27. Hakeem FF, Bernabé E, Sabbah W. Association between oral health and frailty among American older adults. J Am Med Dir Assoc. 2021;22(3):559–e563552.
28. Blodgett J, Theou O, Kirkland S, Andreou P, Rockwood K. Frailty in NHANES: comparing the frailty index and phenotype. Arch Gerontol Geriatr. 2015;60(3):464–70.
29. Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, O'Brien WL, Bassett DR Jr., Schmitz KH, Emplaincourt PO, et al. Compendium of physical activities: an update of activity codes and MET intensities. Med Sci Sports Exerc. 2000;32(9 Suppl):S498–504.
30. Biecek P. DALEX: explainers for complex predictive models in R. J Mach Learn Res. 2018;19(1):3245–9.
31. Huang AA, Huang SY. Increasing transparency in machine learning through bootstrap simulation and shapely additive explanations. PLoS ONE. 2023;18(2):e0281922.
32. Guan C, Ma F, Chang S, Zhang J. Interpretable machine learning models for predicting venous thromboembolism in the intensive care unit: an analysis based on data from 207 centers. Crit Care (London England). 2023;27(1):406.
33. Huang AA, Huang SY. Use of machine learning to identify risk factors for insomnia. PLoS ONE. 2023;18(4):e0282622.
34. Huang AA, Huang SY. Use of machine learning to identify risk factors for coronary artery disease. PLoS ONE. 2023;18(4):e0284103.
35. Wang Z, Zhang L, Huang T, Yang R, Cheng H, Wang H, Yin H, Lyu J. Developing an explainable machine learning model to predict the mechanical ventilation duration of patients with ARDS in intensive care units. Heart Lung: J Crit Care. 2023;58:74–81.
36. Jayanama K, Theou O, Godin J, Mayo A, Cahill L, Rockwood K. Relationship of body mass index with frailty and all-cause mortality among middle-aged and older adults. BMC Med. 2022;20(1):404.
37. Chauhan S, Langstraat CL, Fought AJ, McGree ME, Cliby WA, Kumar A. Relationship between frailty and nutrition: refining predictors of mortality after primary cytoreductive surgery for ovarian cancer. Gynecol Oncol. 2024;180:126–31.
38. Sobhani A, Sharifi F, Fadayevatan R, Kamrani AAA, Moodi M, Khorashadizadeh M, Kazemi T, Khodabakhshi H, Fakhrzadeh H, Arzaghi M, et al. Low physical activity is the strongest factor associated with frailty phenotype and frailty index: data from baseline phase of Birjand longitudinal aging study (BLAS). BMC Geriatr. 2022;22(1):498.
39. Zimmer Z, Saito Y, Theou O, Haviva C, Rockwood K. Education, wealth, and duration of life expected in various degrees of frailty. Eur J Ageing. 2021;18(3):393–404.
40. Wightman H, Quinn TJ, Mair FS, Lewsey J, McAllister DA, Hanlon P. Frailty in randomised controlled trials for dementia or mild cognitive impairment measured via the frailty index: prevalence and prediction of serious adverse events and attrition. Alzheimers Res Ther. 2023;15(1):110.
41. Wong TY, Massa MS, O'Halloran AM, Kenny RA, Clarke R. Cardiovascular risk factors and frailty in a cross-sectional study of older people: implications for prevention. Age Ageing. 2018;47(5):714–20.
42. Fujisawa C, Umegaki H, Sugimoto T, Huang CH, Fujisawa H, Sugimura Y, Kuzuya M, Toba K, Sakurai T. Older adults with a higher frailty index tend to have electrolyte imbalances. Exp Gerontol. 2022;163:111778.
43. Jang J, Jung H, Shin J, Kim DH. Assessment of frailty index at 66 years of age and association with age-Related diseases, disability, and death over 10 years in Korea. JAMA Netw Open. 2023;6(3):e2248995.
44. Gobbens RJ, Luijkx KG, Wijnen-Sponselee MT, Schols JM. Toward a conceptual definition of frail community dwelling older people. Nurs Outlook. 2010;58(2):76–86.
45. Kochlik B, Stuetz W, Pérès K, Pilleron S, Féart C, García García FJ, Bandinelli S, Gomez-Cabrero D, Rodriguez-Mañas L, Grune T, et al. Associations of fat-soluble micronutrients and redox biomarkers with frailty status in the FRAILOMIC initiative. J cachexia Sarcopenia Muscle. 2019;10(6):1339–46.
46. Kaiser M, Bandinelli S, Lunenfeld B. Frailty and the role of nutrition in older people. A review of the current literature. Acta bio-medica: Atenei Parmensis. 2010;81(Suppl 1):37–45.
47. Das A, Cumming RG, Naganathan V, Blyth F, Ribeiro RV, Le Couteur DG, Handelsman DJ, Waite LM, Simpson SJ, Hirani V. Prospective associations between dietary antioxidant intake and frailty in older Australian men: the concord health and ageing in men project. Journals Gerontol Ser Biol Sci Med Sci. 2020;75(2):348–56.
48. Huang AA, Huang SY. Quantification of the effect of vitamin E intake on depressive symptoms in united States adults using restricted cubic splines. Curr Dev Nutr. 2023;7(2):100038.
49. Zhou J, Huang P, Liu P, Hao Q, Chen S, Dong B, Wang J. Association of vitamin D deficiency and frailty: A systematic review and meta-analysis. Maturitas. 2016;94:70–6.
50. Ghoreishy SM, Asoudeh F, Jayedi A, Mohammadi H. Fruit and vegetable intake and risk of frailty: A systematic review and dose response meta-analysis. Ageing Res Rev. 2021;71:101460.
51. Fung TT, Struijk EA, Rodriguez-Artalejo F, Willett WC, Lopez-Garcia E. Fruit and vegetable intake and risk of frailty in women 60 years old or older. Am J Clin Nutr. 2020;112(6):1540–6.
52. Kojima G, Avgerinou C, Iliffe S, Jivraj S, Sekiguchi K, Walters K. Fruit and vegetable consumption and frailty: A systematic review. J Nutr Health Aging. 2018;22(8):1010–7.
53. Hu K, Jin L, Yang Y, Wu L, Xie G, Wu X. The relationship between fruit and vegetable intake and frailty: data from NHANES 2007–2018. Heliyon. 2024;10(19):e38053.
54. Rashidi Pour Fard N, Amirabdollahian F, Haghighatdoost F. Dietary patterns and frailty: a systematic review and meta-analysis. Nutr Rev. 2019;77(7):498–513.
55. Coelho-Júnior HJ, Trichopoulou A, Panza F. Cross-sectional and longitudinal associations between adherence to mediterranean diet with physical performance and cognitive function in older adults: A systematic review and meta-analysis. Ageing Res Rev. 2021;70:101395.
56. Shivappa N, Stubbs B, Hebert JR, Cesari M, Schofield P, Soysal P, Maggi S, Veronese N. The relationship between the dietary inflammatory index and incident frailty: A longitudinal cohort study. J Am Med Dir Assoc. 2018;19(1):77–82.
57. Yoh K, Ikeda K, Horie K, Inoue S. Roles of Estrogen, Estrogen receptors, and Estrogen-Related receptors in skeletal muscle: regulation of mitochondrial function. Int J Mol Sci 2023, 24(3).
58. Williams DR, Mohammed SA. Discrimination and Racial disparities in health: evidence and needed research. J Behav Med. 2009;32(1):20–47.
59. Popkin BM, Reardon T. Obesity and the food system transformation in Latin America. Obes Reviews: Official J Int Association Study Obes. 2018;19(8):1028–64.
60. Ronksley PE, Brien SE, Turner BJ, Mukamal KJ, Ghali WA. Association of alcohol consumption with selected cardiovascular disease outcomes: a systematic review and meta-analysis. BMJ (Clinical Res ed). 2011;342:d671.
61. Xu KH, Li L, Jia SL, Li Q, Hao JX, Ma S, He ZK, Wan QQ, Cai YF, Li ZT, et al. Association of tooth loss and diet quality with acceleration of aging: evidence from NHANES. Am J Med. 2023;136(8):773–e779774.
62. Kim D, Park Y. Association between the Dietary Inflammatory Index and Risk of Frailty in Older Individuals with Poor Nutritional Status. *Nutrients* 2018, 10(10).

Publisher's note