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Healthy eating index and bone health markers in adults with metabolically healthy and unhealthy obese phenotypes

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Abstract

Background: The Healthy Eating Index (HEI) estimates the diet quality, and low HEI scores are associated with adverse bone outcomes. However, the relationship between HEI scores and bone health in individuals who are obese but otherwise healthy or obese with comorbidities remains unclear.

Objective: We aimed to evaluate the association of HEI scores with bone mineral density (BMD), bone regulating hormones and bone turnover markers in individuals with metabolically healthy obese (MHO) and metabolically unhealthy obese (MUO) phenotypes.

Methods: This was a cross-sectional analysis of 122 adults who were overweight or obese. A questionnaire was completed to obtain demographic data. Body composition and BMD were assessed by a Dual Energy X-Ray Absorptiometry (DXA) exam. The HEI scores and dietary components were calculated using a 24-h dietary recall. Blood samples were collected for the analysis of serum 25-hydroxyvitamin D (s25OHD), total osteocalcin (OC), parathyroid hormone (PTH), and C-terminal telopeptide (CTx) concentrations. The MHO and MUO phenotypes were classified according to the absence or presence of metabolic abnormalities.

Results: The sample mean age was 37.91 ± 12.66 years, 50.8% were men, mean body mass index (BMI) was 30.01 ± 4.63 kg/m^2, and 45.9% were classified as the MUO phenotype. The mean HEI scores were 54.42 ± 16.25 and 61.48% had low-diet quality. HEI scores were positively associated with s25OHD in the MUO phenotype group (β = 0.194, 95%CI = 0.038–0.350, p =

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Authors contribution

LGS: HEI calculation, data analysis, writing of original draft, reviewing, editing, final approval of version to be published. MC: data collection, reviewing, editing, final approval of version to be published. RD: data collection, reviewing, editing, final approval of version to be published. DS: Studies coordination, obtaining funding, training personnel, reviewing, editing, final approval of version to be published.

Disclosure statement

The authors report no conflict of interest to report.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Deeptha Sukumar reports financial support was provided by American Heart Association. Deeptha Sukumar reports financial support was provided by Drexel University.

Appendix A. Supplementary data

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0.016). Certain dietary score components, such as fruits, seafood and plant protein, added sugars, whole grains, and fatty acids were also associated with bone health markers. However, HEI scores were not associated with BMD measures, neither with other bone regulating hormones and turnover markers.

Conclusion: There was a positive association between HEI scores and s25OHD in adults who were overweight or obese with MUO phenotype. Additionally, the adequate consumption of specific food groups may benefit bone mass and metabolism. These results emphasize the importance of lifestyle interventions encouraging healthy eating habits to prevent s25OHD deficiency, poor bone health, and cardiometabolic complications.

Keywords

Diet; Bone health; 25-Hydroxyvitamin D; Obesity; Bone turnover markers

1. Introduction

Aging is related to hormonal alterations, higher inflammation, and bone remodeling imbalance which all together contribute to body composition changes as fat gain and bone loss. These factors increase the risk of bone fractures, development of osteoporosis, and mortality in the elderly population [1,2]. Osteoporosis, the most common chronic bone disease, is characterized by low bone mineral density (BMD) and has been considered a critical public health problem worldwide [3,4] as it can lead to financial burden of bone fractures [5] and shares pathophysiological mechanisms with cardiovascular diseases (CVD) [6, 7].

The complex interplay between bone and cardiometabolic health has recently gained immense attention [8,9]. Growing evidence have shown the association of altered bone health markers, such as serum 25-hydroxyvitamin D (s25OHD) [10,11], serum osteocalcin (OC) [12–14], serum parathyroid hormone (PTH) [15,16], and C-terminal telopeptide concentrations (CTx) [17], with adiposity and cardiometabolic risk. Moreover, the presence of low s25OHD and high PTH were significantly higher in individuals with overweight or obesity with the presence of metabolic abnormalities, classified as the metabolically unhealthy obese (MUO) phenotype, compared to those with the metabolically healthy obese (MHO) phenotype, indicating that the MUO phenotype is a potential risk group for the emergence of metabolic bone diseases [18]. In accordance, Sukumar et al. [19] demonstrated that the MUO phenotype group had lower OC and higher PTH concentrations than those with the MHO phenotype. Given that both poor bone health and cardiometabolic risk are inflammatory age-related conditions associated with reduced life quality and expectancy [8,9], a better understanding of their risk factors in adults who are overweight or obese may help to develop effective strategies for the prevention of chronic diseases later in life.

Diet is an important modifiable risk factor of chronic metabolic diseases [20] as it modulates inflammation [21,22]. Unhealthy eating habits with excessive intake of saturated fat and sugar may activate the NF-kB pathway leading to an altered secretion of cytokines and pro-inflammatory mediators [21,22]. In turn, low-grade inflammation stimulates osteoclasts and inhibits osteoblastic activities, thereby enhancing bone loss [23,24]. Alternatively, the

adherence to a healthy dietary pattern that is rich in nutrient-dense foods can beneficially influence bone [25,26] and cardiometabolic health [27,28].

The Healthy Eating Index (HEI) is a measure that estimates an individual's diet quality [29]. An unhealthy diet, as indicated by lower HEI scores, has been linked to adverse bone outcomes [26,30,31] and cardiometabolic risk [32,33]. However, most evidence related to bone health has been restricted to BMD analysis [25,26,31] and studied exclusively in postmenopausal women [31,34]. Importantly, the relationship between HEI and bone health in individuals who are obese but otherwise healthy or obese with comorbidities remains unclear. Hence, further investigations in adults who are overweight or obese, employing bone health markers, are needed to clarify the effects of the dietary quality on bone health status, and its contribution to the onset of cardiometabolic diseases. We aimed to evaluate the association of HEI scores with BMD, bone regulating hormones, and bone turnover markers in adults who were overweight or obese with metabolically health obese (MHO) and metabolically unhealthy obese (MUO) phenotypes. We hypothesized that the HEI scores would be inversely associated with BMD, s25OHD and OC and positively associated with PTH and CTx in MUO phenotype, but not in MHO phenotype.

2. Materials and methods

2.1. Study design and participants

This was a cross-sectional study with secondary data analysis from two larger studies – clinical trial registry #NCT03134417 and #NCT03600675 - carried out at Drexel University. Recruitment methods included advertisements on campus and social media platforms, and potential participants contacted research team by email or telephone for initial screening to ensure eligibility. Data collection was performed from 2015 to 2020. Both studies were approved by the Drexel University Institutional Review Board and all participants read and signed an informed consent form prior to enrollment.

Inclusion criteria for the larger studies included men and women from any ethnicity between the ages of 20 and 70 years old. Exclusion criteria included individuals with preexisting chronic medical conditions, pregnant women, and those who were using medications known to influence bone, blood glucose, lipids, and blood pressure. All participants were provided and instructed to use sunscreen during the clinical trial intervention periods, to mitigate the influence of sun exposure on raising s25OHD.

For the current analysis, we excluded individuals who were >65 years old (n = 3) or who had a body mass index (BMI) <25 kg/m^2 (n = 29), resulting in a final sample of 122 adults who were overweight or obese.

2.2. Sociodemographic and medical history data

A questionnaire was completed to confirm eligibility and to obtain sociodemographic and medical history data such as sex, age, race and ethnicity, tobacco and alcohol habits, medical and clinical concerns, current medications, and supplement use.

2.3. Healthy eating index (HEI) scores

During the baseline visit, a single 24-h dietary recall was administrated by a trained research assistant and/or registered dietitian using the 5-step multiple-pass method [35]. The household measures were converted into grams (g), milligrams (mg), or milliliters (mL) to access energy (kcal) and nutrient intake. Food consumption was analyzed using FoodWorks version 17 software (Long Valley, NJ).

The 2015 Healthy Eating Index (HEI-2015) is the most recent version of HEI which is used to evaluate individual diet quality based on the recommendations proposed on the Dietary Guidelines for Americans (2015–2020) [29,36]. The index is composed by 13 energy-adjusted dietary components (Total Fruits, Whole Fruits, Total Vegetables, Greens and Beans, Whole Grains, Dairy, Total Protein Foods, Seafood and Plant Proteins, Fatty acids, Refined Grains, Sodium, Added Sugars, and Saturated Fats). Of these, 9 components are recommended to be included in a healthy diet and 4 components should be consumed with moderation. The total HEI-2015 score is calculated by summing up the scores of each component, ranging from zero to 100. A higher HEI score indicates a higher intake of healthy foods and a lower intake of foods that should be consumed in moderation. Overall scores above 90 are considered high-quality diets, and scores below 60 are considered low-quality diets [29].

2.4. Bone regulating hormones and turnover markers

Blood samples were collected after ≥8 h of fasting by a licensed phlebotomist. Serum was stored at −80 °C until the analysis of 25-hydroxyvitamin D (s25OHD), total osteocalcin (OC), parathyroid hormone (PTH), and C-terminal telopeptide (CTx). Serum s25OHD was measured by enzyme immunoassay (EIA) from Immunodiagnostic Systems Inc. (Gaithersburg, MD, coefficient of variation (CV) < 8.1%). Serum PTH samples were analyzed using an intact PTH enzyme-linked immunosorbent assay (ELISA) (ALPCO, Salem, NH, CV <6.1%). Serum total OC (Immunodiagnostic Systems Inc., Gaithersbug, MD, CV <5.1%) and CTx (R&D Systems, Minneapolis, MN, CV <10.9%) were also analyzed with ELISAs.

The s25OHD insufficiency (<20 ng/mL) and deficiency (<12 ng/mL) were classified using the cutoff points proposed by the Institute of Medicine [37]. The 25th percentile of the sample (11.43 ng/mL) was used to classify low values of total OC because there are no established cutoff points in the literature [38]. Elevated PTH was defined as serum PTH >65 pg/mL [39].

2.5. Anthropometric and body composition measurements

All measurements were performed in triplicate by a trained research assistant during the visit. Body weight was measured using a Seca 700 Physician's Balance Beam Scale (Chino, CA, USA) with minimal clothing and no shoes. A stadiometer attached to the scale was used to assess height to the nearest 0.5 cm. BMI was calculated by dividing weight (kg) by height squared (m^2). Waist circumference (WC) was measured with a non-stretch tape measure (Health Mobius® Circumference (Girth) measuring Tape-Body Tape Measure) in a horizontal plane around the torso, equidistant between the lowest rib and the iliac crest.

Bone mineral density (BMD), body fat %, and trunk fat % were examined by Dual Energy X-ray Absorptiometry (DXA) (Lunar iDXA, enCORE Software Version 15, GE Healthcare, Little Chalfont, United Kingdom).

2.6. Classification of metabolically healthy obese (MHO) and metabolically unhealthy obese (MUO) phenotypes

Participants were classified into two groups according to the absence or presence of metabolic abnormalities (MHO and MUO). The MHO phenotype group had zero or one out of three of the following characteristics: waist circumferences for men (>102 cm) and women (>88 cm), trunk fat % above the sample median, and total body fat % above the sample median. The MUO phenotype had two or all these characteristics [19].

2.7. Data analysis

The Shapiro-Wilk test, graphical analysis and asymmetry coefficients were used to verify the normality of the data. Results were displayed as mean ± standard deviation (SD) or percentage (%). A Student's t-test or Mann-Whitney *U* test, and ANOVA with Tukey's test for post-hoc analysis or Kruskal-Wallis H test were performed for group comparisons according to the normality of the variable. Pearson's chi-square test was used to determine between-group differences for categorical variables. The associations of HEI-2015 scores and dietary components (exposure) with BMD and bone turnover markers (s25OHD, OC, PTH, CTx) (outcome) in the total sample and each group (MHO and MUO) were evaluated through multivariable linear regression models. Dependent variables with non-parametrical distribution (OC, PTH, and CTx) were log transformed. The models were adjusted by potential confounders such as age, sex, and fat mass. The analyses were carried out in the Stata® version 14 (StataCorp LP, College Station, TX, USA). For all hypotheses, $p < 0.05$ was considered significant.

3. Results

The sample mean age was 37.91 ± 12.66 years, 50.8% were men, mean BMI was 30.01 ± 4.63 kg/m^2, and 45.9% (n = 56) were classified with the MUO phenotype. The MUO phenotype group was older (42.00 ± 12.91 vs 34.33 ± 11.38 years, $p = 0.001$) and had more women (66.7% vs 33.3%, $p < 0.001$) (Table 1).

The MUO phenotype group had higher weight, BMI, WC, total and trunk fat masses; and lower total BMD compared to the MHO phenotype ($p < 0.05$). The sample mean HEI scores were 54.42 ± 16.25 and 61.48% had low-diet quality (overall scores of 0–59). There were no significant differences in HEI scores and its dietary components between MHO and MUO phenotypes (Table 1).

The mean s25OHD was 27.11 ± 7.77 ng/mL, OC was 20.58 ± 18.83 ng/mL, PTH was 61.08 ± 31.63 pg/mL, and CTx was 0.51 ± 0.27 ng/mL (Table 1). In addition, 20.51% of the sample showed insufficiency/deficiency of s25OHD, 24.8% had lower OC (3.61–11.43 ng/mL), and 31.62% had elevated PTH (65.27–197.04 pg/mL) (Data not shown).

3.1. Radar graph of each dietary score component contribution

Fig. 1 shows the radar graph depicting the percentage of each component food score contribution to the maximum possible score in the total sample and according to the MHO and MUO phenotypes. Components with the highest scores were total protein, greens and beans, fatty acids, and added sugars.

3.2. HEI scores and its dietary components

Table 2 shows the means of dietary score components by tertiles of HEI. Individuals with the highest diet quality (third tertile) consumed significantly more of the healthy dietary components, except for total protein, and less of the consume-in-moderation dietary components, compared to those with the lowest diet quality (first tertile) ($p < 0.05$). Similar results were found across HEI tertiles within the MHO and MUO phenotypes groups. In addition to total protein, there were also no significant differences across HEI tertiles for dairy and added sugars in the MHO phenotype, and for total fruits and added sugars in the MUO phenotype.

3.3. HEI scores and bone health markers

Table 3 shows the means of bone health markers by tertiles of HEI. Individuals with the highest diet quality (third tertile) had higher s25OHD concentrations than those with the lowest diet quality (first tertile) in the total sample (30.10 ± 8.31 vs 25.84 ± 6.77) and in the MUO phenotype group (32.06 ± 10.05 vs 23.09 ± 5.83).

After adjustments, HEI scores were positively associated with s25OHD only in MUO phenotype group, regardless of age, sex, and fat mass ($\beta = 0.194$, 95% CI = 0.038–0.350, $p = 0.016$). HEI scores were not associated with BMD measures, nor with other bone regulating hormones and turnover markers (OC, PTH, and CTx) (Table 4).

3.4. Dietary score components and bone health markers

Certain dietary score components were associated with bone health markers. In the total sample, the intakes of whole fruits were directly associated with s25OHD, seafood and plant protein were directly associated with OC, added sugars was directly associated with PTH, and whole grains were inversely associated with CTx. In the MHO phenotype group, total protein and seafood and plant protein were directly associated with OC, whole fruits were inversely associated with total BMD, and refined grains were inversely associated with L2-L4 BMD. In the MUO phenotype group, seafood and plant protein, total fruits, whole fruits, and fatty acids were directly associated with s25OHD, greens and beans and added sugars were inversely and directly associated with OC, respectively (Supplementary Table 1).

4. Discussion

Our results showed that higher HEI scores, indicating a healthier diet, were associated with higher s25OHD in individuals with a MUO phenotype. Among the 13 dietary components of HEI, the adherence to the recommended intake of seafood and plant protein, total fruits, whole fruits, and fatty acids were also associated with higher s25OHD in the MUO

phenotype group. In the total sample, the intake of whole fruits was positively associated with s25OHD, seafood and plant protein were directly associated with OC, added sugars were directly associated with PTH, and whole grains were inversely associated with CTx. HEI scores were not associated with BMD measures, nor with other bone regulating hormones and turnover markers (OC, PTH, CTx).

Our findings demonstrated that HEI scores were positively associated with s25OHD in the MUO phenotype group. The hormone s25OHD plays essential role in bone metabolism by regulating the homeostasis of calcium and phosphorus. The insufficiency and deficiency of s25OHD is a major public health concern with increasing prevalence globally [40]. Low s25OHD concentrations are characterized by mineralization defect in the skeleton [41] and are associated with higher risk of bone fractures [42], bone diseases [43], cardiometabolic alterations [44–46], and inflammation [47,48]. It is estimated that 80–90% of s25OHD in circulation is obtained through cutaneous synthesis after solar exposure, while only 10–20% is obtained through consumption of foods high in vitamin D, such as fortified dairy, fish, egg yolks, and mushrooms [41, 49]. However, there are evidence that the dietary intake of vitamin D is directly associated with s25OHD concentrations [44,50,51]. Similar to our findings, previous researchers have shown a positive association between healthy dietary patterns and s25OHD [52,53], being crucial for the prevention of hypovitaminosis D and chronic bone diseases. In geographical locations where the latitude is between 40° North and 40° South there is elevated and enough UVB radiation to produce sufficient endogenous s25OHD synthesis throughout the year [41,54]. However, in recent years, the prevalence of s25OHD deficiency has increased even in tropical and sunny countries [40,55]. This may be attributed to the increasing incidence of skin cancer caused by excessive exposure to sunlight [56] and other influencing factors that may reduce s25OHD synthesis and absorption, such as sunscreen and clothing habits, sedentary behavior, pollution, skin pigmentation, adiposity, genetic and ethnic aspects [57–60], reinforcing the importance of a healthy and balanced diet with adequate vitamin D intake for maintenance of normal s25OHD status. Additionally, the adherence to a healthier dietary pattern and an increase in s25OHD may benefit the reversal of the MUO phenotype and the reduction of cardiometabolic risk [27,61].

In the MUO phenotype group, the consumption of certain healthy dietary score components related to vitamin D metabolism, such as seafood and plant protein, total fruits, whole fruits, and fatty acids were also directly associated with s25OHD, complementing the main result found between HEI scores and s25OHD in the MUO, but not in the MHO phenotype. Some types of seafood, such as cold-water fatty fishes (e.g., tuna, sardines, salmon, and anchovies) are good sources of vitamin D [41,49]. Fruits and vegetables are rich in nutritional determinants for bone health (e.g., vitamins, minerals, and antioxidants) that may affect bones through several mechanisms, including combating oxidative stress-induced bone loss, bone structure changes, bone metabolism rate, the endocrine and/or paracrine system, calcium homeostasis and possibly other bone-active minerals [62,63]. Fan et al. [30] showed that a higher intake of total and whole fruits decreased the odds of osteoporosis in older adults, corroborating with our findings. Moreover, since vitamin D is a liposoluble vitamin, the consumption of fatty acids improves its absorption [64]. Nutrients with anti-inflammatory properties such as polyunsaturated (PUFA) and monounsaturated (MUFA)

fatty acids also alleviate inflammation and exert beneficial effects on bone turnover by diminishing osteoclast and/or enhancing osteoblast activities [65,66].

In the total sample, dietary score components were also associated with bone regulating hormones and bone turnover markers. The intake of whole fruits was directly associated with s25OHD, seafood and plant protein were directly associated with OC, added sugars were directly associated with PTH, and whole grains were inversely associated with CTx. Serum OC is a non-collagenous protein expressed by osteoblasts that acts in bone matrix to regulate mineralization [67]. The higher consumption of dietary protein has been suggested to favorably affect OC [68,69] and bone health [70], supporting our findings. Dietary protein can also reduce bone loss by increasing the secretion of insulin-like growth factor I (IGF-I), an important hormone for bone formation [70,71]. The PTH is a calciotropic hormone inversely related to s25OHD that modulates osteoblasts activities [72] and has been shown to be directly associated with proinflammatory cytokines [73]. Excessive intake of sugar is associated with detrimental effects on bone formation and remodeling by many mechanisms, such as increasing systemic inflammation, enhancing urinary calcium and magnesium excretion, impairing osteoblastic proliferation, and decreasing active 1, 25-dihydroxyvitamin D, which leads to reduction of calcium intestinal absorption [74]. Taken together, these factors may also influence the increase of PTH in the circulation. The CTx is a marker of osteoclast activity and bone resorption originated from collagen degradation [75]. Whole grains are extremely rich in dietary fiber [36], a nutrient that has been associated with lower bone loss and higher BMD [76,77]. Consistent with our results, Langsetmo et al. [78] observed that the dietary pattern composed by whole grains, fruits, vegetables, legumes, and fish was associated with lower CTx concentrations. Therefore, the adoption of healthy eating habits can help in the preservation of overall bone health in adults who are overweight or obese.

Our results did not support the associations of HEI scores with BMD measures, other bone regulating hormones, and bone turnover markers (OC, PTH, and CTx). Likewise, Hamidi et al. [34] did not observe significant results in the relationship between HEI-2005 and bone turnover markers (serum bone-specific alkaline phosphatase, BAP, and urinary N-telopeptides/creatinine, uNTx/Cr) in postmenopausal women. Additional research with elderly Brazilian women found that poorer diet quality was associated with higher levels of bone remodeling markers (BAP and CTx) but was not significant associated with BMD [79]. In contrast, other studies demonstrated positive associations between diet quality and BMD measures [25,26,31]. A possible explanation for this discrepancy in the literature may be related to differences in sample characteristics and methodologies of diet quality evaluation. In our sample, bone health measures, HEI scores and its dietary components did not significantly differ between the MUO and MHO phenotypes, which may have hidden significant results. In addition, it is possible that long-term unhealthy eating habits may have a greater impact on bone health leading to bone compromise at older ages as compared to a younger age in this analysis. Due to this, longitudinal investigations are needed to better understand the role of diet in reducing bone diseases risk, especially in individuals who are overweight or obese, and therefore have a higher risk for s25OHD deficiency [80,81] and bone loss [82, 83].

Limitations of our work include its cross-sectional design, which limited the ability to establish causality. Second, the small sample size affected generalizability and prevented the findings to be extrapolated; thus, future prospective studies with representative populations are required to confirm our findings. Third, we used a single 24-h dietary recall to assess nutrient intake and calculate HEI scores which may not have reflected the usual consumption. Fourth, the HEI scores may not be the best overall diet quality-assessment tool in relation to bone health; thereby, it is necessary to create and validate a proper index. Finally, while efforts were made to limit confounding variables for s25OHD, ultimately, we were unable to measure and adjust regression models accordingly.

Strengths of this study include that to the best of our knowledge, this is the first analysis evaluating the relationship between HEI scores and multiple components of bone health including BMD, bone regulating hormones, and bone turnover biomarkers in adults who were overweight or obese. We used the HEI-2015, the most updated version of the index based on the Dietary Guideline for Americans (2015–2020) [36]. The sample was composed exclusively by adults who were overweight or obese, and the statistical analyses were performed according to the absence and presence of metabolic abnormalities (MHO and MUO phenotypes). Body composition and BMD measures were analyzed by dual energy X-ray absorptiometry, a gold-standard method, and the regression models were controlled for fat mass. Our work provides novel information for the development of effective and sustainable public health policies to promote bone and cardiometabolic health.

5. Conclusions

In conclusion, there was a positive association between HEI scores and s25OHD in adults who were overweight or obese with a MUO phenotype. Additionally, the adequate consumption of healthy food groups, such as fruits, seafood and plant protein, added sugars, whole grains, and fatty acids may benefit bone mass and metabolism. These results emphasize the importance of lifestyle interventions encouraging healthy eating habits to prevent s25OHD deficiency, poor bone health, and cardiometabolic complications, mainly in individuals with obesity-related metabolic abnormalities.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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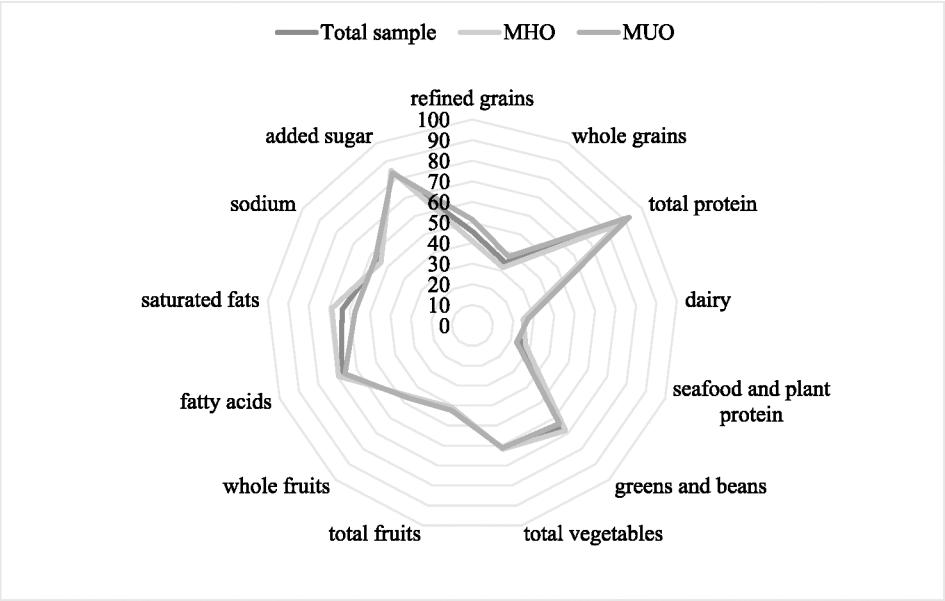

Fig. 1.

Radar graph depicting the percentage of each component food score contribution to the maximum possible score in adults with metabolically healthy obese (MHO) and metabolically unhealthy obese (MUO) phenotypes.

Table 1

Participants characteristics.

Variables	Total sample (N = 122)	MHO \(N = 56)	MUO (N = 66)	p-value
Demographics				
Age (years)[2]	37.91 ± 12.66	34.33 ± 11.38	42.00 ± 12.91	0.001*
Sex (%)[3]	F: 49.2; M: 50.8	F: 33.3; M: 74.2	F: 66.7; M: 25.8	<0.001*
Body measures				
Weight (lbs)[2]	196.10 ± 35.84	192.26 ± 31.78	200.30 ± 39.68	0.002*
BMI (kg/m^2)[2]	30.01 ± 4.63	28.51 ± 3.67	31.72 ± 5.04	<0.001*
WC (cm)[2]	96.02 ± 12.23	92.39 ± 11.68	100.17 ± 13.78	<0.001*
Total FM (%)[1]	35.94 ± 9.31	29.25 ± 6.62	43.58 ± 5.09	<0.001*
Trunk fat (%)[1]	39.78 ± 10.07	32.71 ± 7.06	47.85 ± 6.14	<0.001*
Bone health markers				
s25OHD (ng/mL)[1]	27.11 ± 7.77	27.17 ± 6.79	27.04 ± 8.82	0.862
OC (ng/mL)[2]	20.58 ± 18.83	23.80 ± 23.77	16.91 ± 9.78	0.334
PTH (pg/mL)[2]	61.08 ± 31.63	57.97 ± 33.51	64.62 ± 29.26	0.078
CTx (ng/mL)[2]	0.51 ± 0.27	0.55 ± 0.31	0.47 ± 0.22	0.579
Total BMD[1]	1.28 ± 0.12	1.31 ± 0.12	1.24 ± 0.11	0.002*
L2-L4 BMD[1]	1.32 ± 0.14	1.33 ± 0.13	1.30 ± 0.15	0.460
Total hip BMD[1]	1.13 ± 0.13	1.15 ± 0.12	1.09 ± 0.14	0.067
Diet quality				
HEI-2015 score[1]	54.42 ± 16.25	53.94 ± 16.28	54.96 ± 16.36	0.864
A - Overall scores of 90–100 (%)	0.0	0.0	0.0	–
B - Overall scores of 80–89 (%)	7.58	7.38	7.14	–
C - Overall scores of 70–79 (%)	7.58	7.38	7.14	–
D - Overall scores of 60–69 (%)	20.49	22.73	17.86	–
F - Overall scores of 0–59 (%)	61.48	62.12	60.71	–
Adequacy				
Whole grains (oz/1000 kcal)[2]	0.91 ± 1.5	0.88 ± 1.59	0.94 ± 1.39	0.400
Total protein (oz/1000 kcal)[2]	5.22 ± 3.89	5.61 ± 4.55	4.72 ± 2.82	0.389
Dairy (cup/1000 kcal)[2]	0.36 ± 0.46	0.37 ± 0.54	0.35 ± 0.35	0.922
Sea food and plant protein (cup/1000 kcal)[2]	0.25 ± 0.44	0.29 ± 0.53	0.19 ± 0.29	0.608
Green and beans (cup/ 1000 kcal)[2]	0.62 ± 0.78	0.65 ± 0.88	0.58 ± 0.65	0.284
Total vegetables (cup/ 1000 kcal)[2]	0.96 ± 0.90	0.99 ± 0.97	0.92 ± 0.81	0.401
Total fruits (cup/1000 kcal)[2]	0.47 ± 0.66	0.46 ± 0.62	0.49 ± 0.72	0.779
Whole fruits (cup/1000 kcal)[2]	0.41 ± 0.64	0.40 ± 0.58	0.42 ± 0.71	0.478

Variables	Total sample (N = 122)	MHO \(N = 56)	MUO (N = 66)	p-value
Fatty acids (PUFA + MUFA/SFA)[2]	2.05 ± 0.92	2.19 ± 1.03	1.87 ± 0.72	0.527
Moderation				
Saturated fats (% EI)[2]	11.99 ± 4.47	11.43 ± 4.37	12.70 ± 4.54	0.548
Sodium (g/1000 kcal)[1]	1.66 ± 0.65	1.70 ± 0.66	1.60 ± 0.63	0.421
Added sugars (% EI)[2]	6.81 ± 7.39	6.63 ± 6.44	7.04 ± 8.50	0.199
Refined grains (oz/ 1000 kcal)[2]	4.26 ± 3.40	4.46 ± 3.51	4.01 ± 3.27	0.301

BMD, bone mineral density; BMI, body mass index; CTx, C-terminal telopeptide; EI, energy intake; F, female; FM, fat mass; HEI, health eating index; M, male; MHO, metabolically health obese phenotype; MUFA, monounsaturated fatty acids; MUO, metabolically unhealthy obese phenotype; OC, serum osteocalcin; PTH, serum parathyroid hormone; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids; s25OHD, serum 25-hydroxyvitamin D; WC, waist circumference.

Results displayed as mean ± standard deviation (SD) or percentage (%). Student's t-test1 or Mann-Whitney *U* test2 were used for continuous variables according to the normality of the variable. Pearson's chi-square test3 was used for categorical variables (*p < 0.05).

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Table 2

Dietary score components by tertiles (T) of Healthy Eating Index (HEI-2015) score in adults with metabolically healthy obese (MHO) and metabolically unhealthy obese (MUO) phenotypes.

Variables	Total sample (N = 122)			p-value	MHO (N = 56)			p-value	MUO (N = 66)			p-value
	T1	T2	T3		T1	T2	T3		T1	T2	T3	
Adequacy												
Whole grains (oz/1000 kcal)[2]	0.05 ± 0.22[a]	0.89 ± 1.27[b]	1.78 ± 1.91[c]	<0.001*	0.09 ± 0.29[a]	0.70 ± 1.15[b]	1.88 ± 2.17[c]	<0.001*	0.00 ± 0.00[a]	1.09 ± 1.41[b]	1.65 ± 1.57[c]	<0.001*
Total protein (oz/1000 kcal)[2]	5.46 ± 4.41	4.80 ± 3.03	5.42 ± 3.03	0.849	6.61 ± 5.12	4.77 ± 3.13	5.39 ± 5.03	0.490	3.80 ± 2.40	4.82 ± 3.00	5.46 ± 2.91	0.134
Dairy (cup/1000 kcal)[2]	0.23 ± 0.24[a]	0.27 ± 0.32[a]	0.59 ± 0.65[b]	0.010*	0.26 ± 0.25	0.23 ± 0.31	0.61 ± 0.80	0.204	0.17 ± 0.22[a]	0.31 ± 0.33[ab]	0.56 ± 0.38[b]	0.025*
Sea food and plant protein (cup/1000 kcal)[2]	0.09 ± 0.19[a]	0.21 ± 0.37[b]	0.44 ± 0.60[c]	<0.001*	0.09 ± 0.17[a]	0.29 ± 0.42[b]	0.49 ± 0.76[b]	0.004*	0.10 ± 0.21[a]	0.12 ± 0.27[a]	0.37 ± 0.30[b]	0.001*
Green and beans (cup/1000 kcal)[2]	0.22 ± 0.76[a]	0.66 ± 0.51[b]	0.97 ± 0.87[b]	<0.001*	0.33 ± 0.98[a]	0.65 ± 0.45[b]	0.98 ± 0.98[b]	<0.001*	0.07 ± 0.16[a]	0.66 ± 0.59[b]	0.96 ± 0.54[b]	<0.001*
Total vegetables (cup/1000 kcal)[2]	0.48 ± 0.80[a]	0.93 ± 0.59[b]	1.47 ± 1.00[c]	<0.001*	0.59 ± 1.00[a]	0.93 ± 0.53[b]	1.46 ± 1.10[b]	0.001*	0.32 ± 0.33[a]	0.93 ± 0.67[b]	1.48 ± 0.89[b]	<0.001*
Total fruits (cup/1000 kcal)[2]	0.26 ± 0.42[a]	0.47 ± 0.71[a]	0.67 ± 0.76[b]	0.001*	0.18 ± 0.32[a]	0.63 ± 0.86[a]	0.58 ± 0.50[b]	0.004*	0.38 ± 0.52	0.30 ± 0.45	0.79 ± 1.00	0.072
Whole fruits (cup/1000 kcal)[2]	0.16 ± 0.33[a]	0.40 ± 0.65[a]	0.66 ± 0.75[b]	<0.001*	0.15 ± 0.31[a]	0.49 ± 0.79[ab]	0.58 ± 0.50[b]	0.001*	0.18 ± 0.37[a]	0.30 ± 0.45[ab]	0.77 ± 1.02[b]	0.026*
Fatty acids (PUFA + MUFA/SFA)[2]	1.50 ± 0.45[a]	1.99 ± 0.83[b]	2.66 ± 1.00[c]	<0.001*	1.50 ± 0.45[a]	2.22 ± 0.91[b]	2.89 ± 1.13[c]	<0.001*	1.51 ± 0.47[a]	1.73 ± 0.67[a]	2.37 ± 0.74[b]	<0.001*
Moderation												
Saturated fats (% EI)[2]	14.24 ± 4.43[a]	12.27 ± 4.35[a]	9.44 ± 3.23[b]	<0.001*	14.30 ± 4.77[a]	10.93 ± 3.30[b]	8.90 ± 2.97[b]	<0.001*	14.17 ± 4.05[a]	13.74 ± 4.95[a]	10.15 ± 3.51[b]	0.015*
Sodium (g/1000 kcal)[1]	2.05 ± 0.49[a]	1.52 ± 0.56[b]	1.42 ± 0.70[b]	<0.001*	2.11 ± 0.51[a]	1.56 ± 0.54[b]	1.41 ± 0.73[b]	<0.001*	1.96 ± 0.46[a]	1.47 ± 0.60[ab]	1.42 ± 0.69[b]	0.023*
Added sugars (% EI)[2]	7.92 ± 7.17[a]	8.63 ± 9.54[a]	3.84 ± 3.04[b]	0.014*	8.08 ± 8.15	7.91 ± 6.42	3.90 ± 2.80	0.087	7.70 ± 5.73	9.42 ± 12.26	3.75 ± 3.41	0.066
Refined grains (oz/1000 kcal)[2]	6.21 ± 3.55[a]	4.12 ± 3.32[b]	2.46 ± 2.13[c]	<0.001*	5.78 ± 3.44[a]	5.10 ± 3.98[a]	2.54 ± 2.17[b]	0.002*	6.90 ± 3.70[a]	3.05 ± 1.98[b]	2.35 ± 2.14[c]	<0.001*

T1, HEI scores ranging from 15.88 to 47.99; T2, from 48.00 to 61.00; T3, from 61.01 to 89.92.

Results displayed as mean ± standard deviation (SD).

ANOVA[1] with Tukey's test for post-hoc analysis or Kruskal-Wallis H^2 test were used according to the normality of the variable (*$p < 0.05$).

[a,b,c] Mean values within a row with unlike superscript letters were significantly different.

Table 3

Bone health markers by teriles (T) of Healthy Eating Index (HEI-2015) score in adults with metabolically healthy obese (MHO) and metabolically unhealthy obese (MUO) phenotypes.

Variables	Total sample (N = 122)			p-value	MHO (N = 56)			p-value	MUO (N = 66)			p-value
	T1	T2	T3		T1	T2	T3		T1	T2	T3	
s25OHD (ng/ mL)[1]	25.84 ± 6.77[a]	25.33 ± 7.15[a]	30.10 ± 8.31[b]	0.036*	27.72 ± 6.85	24.77 ± 7.42	28.43 ± 5.63	0.548	23.09 ± 5.83[a]	25.83 ± 7.05[a]	32.06 ± 10.05[b]	0.008*
OC (ng/ mL)[2]	23.85 ± 15.42	17.80 ± 9.77	20.23 ± 26.46	0.129	26.35 ± 17.30	19.83 ± 9.43	24.83 ± 35.20	0.249	20.20 ± 11.78	15.99 ± 9.96	14.78 ± 6.73	0.578
PTH (pg/ mL)[2]	62.33 ± 33.19	63.31 ± 37.18	56.92 ± 22.25	0.997	62.70 ± 37.00	62.84 ± 39.95	47.45 ± 17.82	0.513	61.80 ± 27.90	63.74 ± 35.62	68.05 ± 22.21	0.418
CTx (ng/ mL)[2]	0.59 ± 0.30	0.47 ± 0.25	0.46 ± 0.23	0.073	0.62 ± 0.36	0.50 ± 0.25	0.51 ± 0.27	0.273	0.54 ± 0.20	0.45 ± 0.26	0.40 ± 0.16	0.271
Total BMD[1]	1.30 ± 0.13	1.27 ± 0.13	1.27 ± 0.10	0.340	1.33 ± 0.12	1.32 ± 0.12	1.28 ± 0.11	0.395	1.26 ± 0.13	1.22 ± 0.13	1.25 ± 0.08	0.593
L2-L4 BMD[1]	1.32 ± 0.15	1.30 ± 0.15	1.33 ± 0.13	0.570	1.33 ± 0.15	1.31 ± 0.12	1.35 ± 0.13	0.664	1.30 ± 0.15	1.29 ± 0.18	1.32 ± 0.14	0.848
Total hip BMD[1]	1.14 ± 0.16	1.12 ± 0.13	1.11 ± 0.11	0.547	1.17 ± 0.14	1.17 ± 0.10	1.11 ± 0.11	0.287	1.10 ± 0.18	1.07 ± 0.13	1.12 ± 0.12	0.643

BMD, bone mineral density; CTx, C-terminal telopeptide; OC, serum osteocalcin; PTH, serum parathyroid hormone; s25OHD, serum 25-hydroxyvitamin D; T1, HEI scores ranging from 15.88 to 47.99; T2, from 48.00 to 61.00; T3, from 61.01 to 89.92.

Results displayed as mean ± standard deviation (SD).

ANOVA[1] with Tukey's test for post-hoc analysis or Kruskal-Wallis H[2] test were used according to the normality of the variable (*$p < 0.05$).

[a,b,c] Mean values within a row with unlike superscript letters were significantly different.

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Table 4

Association between Healthy Eating Index (HEI-2015) score and bone health markers in adults with metabolically healthy obese (MHO) and metabolically unhealthy obese (MUO) phenotypes.

Variables	Total sample (N = 122)		p-value	MHO (N = 56)		p-value	MUO (N = 66)		p-value
	β	95%CI		β	95%CI		β	95%CI	
s25OHD (ng/mL)	0.061	−0.029–0.152	0.185	−0.038	−0.149–0.073	0.498	0.194	0.038–0.350	0.016*
OC (ng/mL)	−0.002	−0.005–0.000	0.077	−0.002	−0.007–0.001	0.171	−0.002	−0.007–0.001	0.209
PTH (pg/mL)	−0.001	−0.003–0.001	0.378	−0.002	−0.006–0.001	0.141	0.004	−0.003–0.004	0.812
CTx (ng/mL)	−0.001	−0.003–0.001	0.318	0.000	−0.004–0.002	0.732	−0.002	−0.005–0.001	0.272
Total BMD	0.000	−0.001–0.001	0.689	0.000	−0.002–0.001	0.495	0.000	−0.001–0.002	0.761
L2-L4 BMD	0.000	−0.002–0.001	0.961	0.001	−0.001–0.003	0.416	−0.001	−0.004–0.002	0.518
Total hip BMD	0.000	−0.001–0.001	0.677	0.000	−0.001–0.002	0.875	0.001	−0.001–0.003	0.474

BMD, bone mineral density; 95% CI, 95% confidence interval; CTx, C-terminal telopeptide; OC, serum osteocalcin; PTH, serum parathyroid hormone; s25OHD, serum 25-hydroxyvitamin D.

Linear regression models adjusted by age, sex, and fat mass % (*p < 0.05). The CTx, OC, and PTH were log transformed.