

Original article

Dietary protein intake and body composition, sarcopenia and sarcopenic obesity: A prospective population-based study

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SUMMARY

Background&aims: Obesity and sarcopenia are major health concerns, particularly among older populations. Dietary protein may help preserve muscle mass and function, but high-protein diets, especially from animal sources, may also increase adipose mass. We investigated associations of total, animal, and plant protein intake with body composition trajectories, sarcopenia, and sarcopenic obesity.

Methods: We included 4576 participants (mean age 65.1 years, 56 % women) from the population-based Rotterdam Study. Dietary protein was measured using food-frequency questionnaires at baseline (2004–2009). Body composition was measured every 4–5 years using dual X-ray-absorptiometry. Handgrip strength (HGS) was assessed starting 2006 using a hydraulic dynamometer. Sarcopenia was determined based on low appendicular skeletal muscle and HGS; and sarcopenic obesity risk based on measures of lean mass, HGS and body fat. Analyses used linear mixed models and generalized estimate equation models.

Results: Higher total protein intake was associated with increased BMI over time (mean difference [95 %-confidence interval (CI)]: 0.86 kg/m² [0.01,1.71] per 5E% increase), and increased fat-mass index (1.33 [0.67,1.99]), body-fat-percentage (4.54[2.76,6.31]), and both gynoid and android fat percentage. Higher protein intake was also associated with a higher sarcopenic obesity risk (−0.85[−1.5,−0.2]), but with a lower sarcopenia risk (odds ratio: 0.62 [0.43,0.90]). These associations were mainly driven by animal protein.

Conclusion: Higher protein intake, particularly from animal food sources, is protective against sarcopenia but also linked to a higher obesity risk. A balanced protein intake advice for older persons should be formulated based on individual needs and health status to prevent sarcopenia, obesity, and sarcopenic obesity.

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1. Introduction

The aging process is generally accompanied by changes in body composition, characterized by increased fat and decreased muscle mass [1]. Such changes have substantial health implications as they increase the risk of obesity and sarcopenia. Obesity is a crucial determinant of many chronic diseases, such as cardiovascular diseases and cancer [2]. Sarcopenia, characterized by the loss of muscle mass, strength, and function, also increases the risk of various adverse health outcomes, including a higher risk of falls, disability, reduced quality of life, and increased risk of premature mortality [3,4]. The co-existence of both sarcopenia and obesity has recently been identified as an imminent threat to the elderly population [5] and remains largely undiagnosed [5,6]. Given the severe consequences and high prevalence of both obesity and sarcopenia, there is an imperative need for research on the combined prevention of obesity and sarcopenia [7].

Dietary protein intake may play a role in sarcopenia and obesity. A high-protein diet has been proposed to help prevent sarcopenia, as dietary protein is a source of essential amino acids (EAAs), crucial for muscle protein synthesis [8]. Muscle strength, often assessed using handgrip strength (HGS), has also been observed to be associated with dietary protein intake [9]. Furthermore, protein intake has generally been suggested to be protective against obesity [10–12]. Studies have demonstrated that high protein intake stimulates intestinal peptide hormones, promoting satiety and consequently reducing overall food intake [10]. Additionally, protein intake has been shown to improve metabolic syndrome markers, including lipid profiling and blood pressure, particularly in overweight and obese patients [11,12]. Higher protein intake also increases diet-induced thermogenesis leading to a higher energy expenditure, which helps prevent weight gain or promote weight loss [13]. Much of the existing evidence is derived from short-term randomized controlled trials (RCTs) with high-protein diets, and there remains a gap in understanding the long-term effects of habitual protein intake on body composition and muscle strength [14]. Furthermore, the impact of protein may differ depending on its source, each having distinct protein quality in bioavailability and EAA profiling. Finally, many prior studies have relied on anthropometric measures, such as waist circumference, as proxies for body composition. Those proxies cannot fully capture muscle versus lean mass or fat distribution, which also represents distinct health threats [15].

To address these gaps, our study aimed to study associations between habitual protein intake derived from animal and plant sources and changes in body composition, HGS, sarcopenia, and sarcopenic obesity. We used repeatedly measured data from a large population-based prospective cohort – the Rotterdam Study. Utilizing Dual X-ray Absorptiometry (DXA) scans, we measured fat-free mass, fat mass, and fat distribution in the central and regional areas.

2. Material & methods

2.1. Study population

This study was embedded in the Rotterdam Study (RS), a large population-based prospective cohort study which started in 1990. The design of the Rotterdam Study has been previously described in detail [16]. The Rotterdam Study has been approved by the Medical Ethics Committee of Erasmus MC (registration number MEC 02.1015) and by the Dutch Ministry of Health, Welfare, and Sport (Population Screening Act WBO, license number 1071272-159521-PG). Written informed consent was obtained from all participants. In the initial study, RS-I, 7,983 residents aged 55 or

older from the Ommoord district in Rotterdam participated in 1990. In 2000, the study was expanded with a second cohort, RS-II, consisting of 3,932 additional participants aged 55 or older. A third extension, RS-III, was initiated in 2006, including 3,932 individuals aged 45 years or older, and a fourth extension (RS-IV) in 2016 included 4000 participants aged 40 years and older. Throughout the study, participants underwent home interviews and physical examinations at baseline and at 4 to 5-year intervals. Home interviews and physical examinations were conducted by trained staff, in our dedicated research center in the Ommoord neighborhood, using standardized protocol consistent across sub-cohorts.

For the current study, the baseline was set at the fifth examination round of RS-I (RS-I-5) and the first examination rounds of RS-II (RS-II-1) and RS-III (RS-III-1), when DXA scanning were introduced in the study (Fig. 1). Of the 8,547 participants still alive and participating in the Rotterdam Study by then, 5,755 had data on dietary protein intake. Of these participants, 4,576 had body composition measured at least once (maximum three times), and a subsample of 4,471 participants had HGS, sarcopenia, and sarcopenic obesity measured at least once (maximum twice) (Fig. 1).

2.2. Protein intake

Protein intake was self-reported using food frequency questionnaires (FFQ). The method used to determine dietary intake for the first and third cohorts differed slightly from the method used for the second cohort. Participants completed a self-administered, semi-quantitative FFQ for the first and third cohorts, including 389 food items. For the second cohort, participants first completed a self-administered FFQ consisting of 170 food items, followed by a structured interview with a dietician to specify food items and identify the frequencies and amounts of consumption. For data from both FFQs, food intake data were converted into energy and nutrient intake according to Dutch Food composition tables (NEVO). Apart from total protein intake, distinctions were made based on protein derived from animal and plant sources. Both FFQs have been validated against other assessment methods [17–19]. For the 170-item FFQ, Pearson's correlation between protein measured by FFQ and protein intake measured by food records was 0.66 for total protein and 0.59 for plant protein, and Spearman's correlation for total protein intake against urinary urea was 0.67 [19]. Participants reporting total energy intake <500 or >5000 kcal/day were considered likely to have misreported and were therefore excluded.

2.3. Body composition

Total body weight was obtained using a digital scale while participants wore lightweight clothing. Height was measured with participants in a standing position, without shoes. DXA scans (Prodigy and iDXA devices, GE Healthcare, Chicago, United States) were used to assess total fat mass, total fat-free mass, appendicular lean mass (ALM), gynoid fat mass, and android fat mass by trained readers. Body mass index (BMI) was calculated as total body weight measured in kilograms divided by height in square meters. Fat mass index (FMI) was calculated as total fat mass in kilograms divided by height in square meters. Fat-free mass index (FFMI) was determined by dividing the total lean mass in kilograms by height in square meters. The gynoid fat percentage was calculated as the proportion of gynoid fat in the total non-bone mass of the gynoid region. The android fat percentage represented the android fat percentage in the total non-bone mass of the android region. Total body fat percentage (BF%) was calculated as the proportion of total fat mass to total body weight. Participants with a BMI ≥ 35 kg/m²

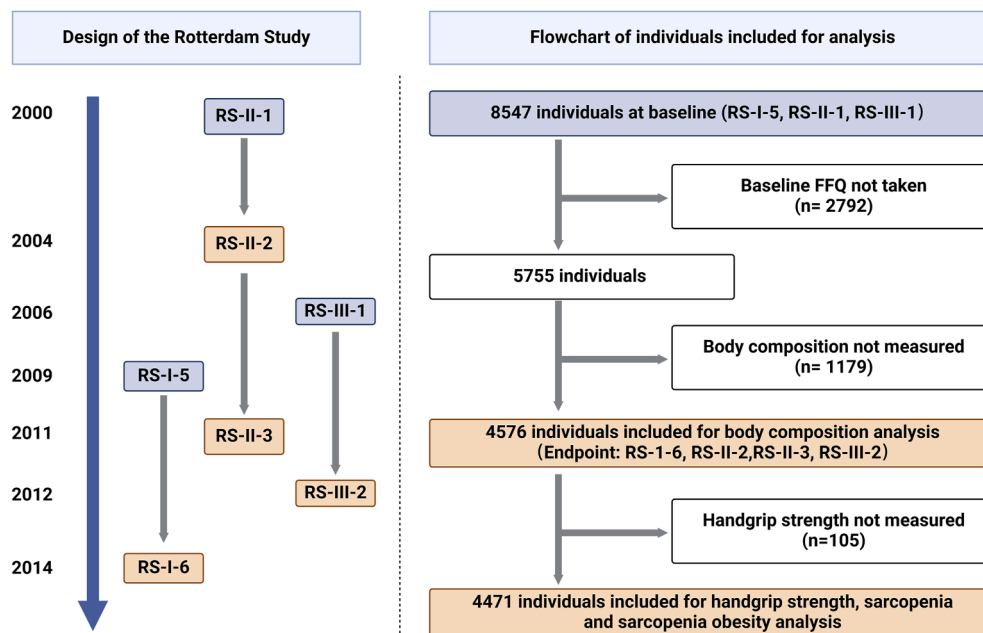


Fig. 1. The design of the Rotterdam Study and flow chart of the study population.

Overview of the Rotterdam Study data and study population used for this study. RS-I-5 and RS-I-6 refer to re-examinations of the original cohort members. RS-II-1 refers to the extension of the cohort with persons from the study district who had become 55 years old since the start of the study or those of 55 years or over who migrated into the study district. RS-II-2 and RS-II-3 refer to re-examinations of the extension cohort. RS-III-1 refers to another extension of the cohort with persons aged 45 years and over living in the study district that had not been examined already (i.e., mainly comprising those aged 45–60 years). RS-III-2 refers to the first re-examination of this third cohort. FFQ = food frequency questionnaire.

were excluded from body composition analysis due to limitations in DXA scan coverage at higher body sizes.

2.4. Handgrip strength and sarcopenia

Peak HGS was measured using a hydraulic hand dynamometer, with the highest value obtained from three attempt records. Sarcopenia was defined according to the updated criteria provided by the European Working Group on Sarcopenia in Older People (EWGSOP2) [20]. Low muscle strength was identified as peak HGS below 27 kg for men or 16 kg for women. Low muscle quantity was determined based on the appendicular skeletal muscle index (ASMI), calculated as the appendicular skeletal lean mass measured by DXA in kilograms divided by height in square meters. An ASMI below 7.0 kg/m² for men or 5.5 kg/m² for women indicated low muscle quantity [20].

2.5. Sarcopenic obesity index

A sarcopenic obesity index was computed using HGS, ALM adjusted to body weight (ALM/W), and BF%. The parameters were selected as recommended by the ESPEN/EASO Consensus [6]. We constructed a continuous index based on sex-specific z-scores for these three variables as the sum of HGS z-score and ALM/W z-score, minus BF% z-score. A higher sum score indicated a lower risk of sarcopenic obesity.

2.6. Covariates

Smoking status (never, past, current) and level of education (primary, lower, intermediate, higher) were assessed during in-home interviews. Daily physical activity was measured using the LASA physical activity questionnaire and a modified version of the Zutphen Study Physical Activity Questionnaire and expressed

in metabolic equivalent of task (MET) hours per week. Cohort-specific z-scores were used to unify physical activity data from different questionnaires. As protein intake is often correlated with other dietary factors, we included a diet quality score reflecting adherence to Dutch dietary guidelines to capture these co-varying effects in a single summary measure [21]. Data on the presence (yes/no) of baseline dyslipidemia (defined as a serum total cholesterol level >6.5 mmol/L or use of lipid-lowering medication), hypertension (defined as use of antihypertensive medication, having a systolic blood pressure ≥140 mmHg or having a diastolic blood pressure ≥90 mmHg), and diabetes (defined as a fasting plasma glucose level ≥7 mmol/L, a non-fasting plasma glucose level ≥11.1 mmol/L or the use of blood glucose-lowering medication), as well as comorbid diseases (chronic kidney disease (defined as having an estimated glomerular filtration rate <60), coronary heart disease, heart failure, stroke, and cancer), were collected by consulting medical records and screening at the research center. The missing value rates for most covariates were lower than 2 %, except for a missing value rate of 7.15 % for physical activity. Missing values were imputed using multiple imputation (n = 10).

2.7. Statistical analysis

The body composition outcomes were measured one to three times during follow-up, while HGS, sarcopenia, and sarcopenic obesity index were measured twice. To account for the repeated measurements of outcomes of interest, we utilized linear mixed models with random intercepts and slopes (i.e., age at the time of measurement). In the first model, total protein intake was included as the exposure; in a second model, animal and plant protein intake were included as the exposure. To account for outcome changes (slope differences) over time, we included a two-way interaction term between age at each follow-up and protein

intake in our models. We employed logistic regression models using a generalized estimating equation to estimate total, animal, and plant protein intake association with prevalent sarcopenia. The multivariable nutrient density substitution model was utilized for all statistical models, which is a method to account for overall energy intake, as well as intake of other macronutrients. This involved including total energy intake (kcal/day), as well as dietary protein, fat, and alcohol intake as percentages of total energy intake (E%) (all include per 5E%). By not including dietary carbohydrate intake, the effect estimates of dietary protein intake can be interpreted as the mean difference in outcome measures per 5E % increase in protein intake at the expense of carbohydrate intake while keeping total energy intake constant. By not including dietary carbohydrate intake, the effect estimates of dietary protein intake can be interpreted as the mean difference in outcome measures per 5E% increase in protein intake at the expense of carbohydrate intake while keeping total energy intake constant. To control for potential confounding factors, we adjusted for age at body composition measurement, sex, sub-cohort, physical activity, smoking, alcohol, level of education, and diet quality in all models. Moreover, splines with 2 knots were added to age in the models as this improved the fit of the model, as shown by the likelihood ratio tests ($p < 0.05$). Dietary animal and plant protein were mutually adjusted for each other.

2.8. Additional analyses

We constructed a separate model, in which we additionally adjusted for prevalent hypertension, dyslipidemia, and diabetes at baseline on top of the main model to investigate if metabolic syndrome substantially influenced the observed associations. We stratified all analyses for sex to explore potential sex-specific associations. To study whether the effects of protein on body composition and sarcopenia outcomes differ by level of physical activity, we tested if the interaction terms of protein with physical activity in the models were significant. We conducted several sensitivity analyses to evaluate the robustness of our main results. First, we repeated the main analyses excluding participants with comorbidities at baseline to assess the potential impact of pre-existing health conditions on the associations between protein intake and body composition measures. Second, we examined the effect of different macronutrient substitutions by including saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), and trans-unsaturated fatty acids (trans-fat) in the models instead of total fat, and lastly by including carbohydrates intake in the models to replace total fat. Lastly, to assess whether associations differed by types of FFQ, we repeated the main analyses stratified by FFQ group: RS1/RS3 (389-item FFQ) versus RS2 (170-item FFQ). All statistical analyses were performed using R version 4.1.1 (The R Foundation for Statistical Computing, Vienna, Austria).

3. Results

The baseline characteristics of the study population ($n = 4,576$) are presented in Table 1. Participants were, on average, 65.1 years old (standard deviation:10.9), and 56.3 % were women. Participants consumed, on average, 1.13 g of protein per kg body weight per day, corresponding to 15.7 % of the total energy intake, which is the similar level compared to other western cohorts [22]. The mean daily plant protein intake was 6.1 E% and 0.45 g/kg body weight, while the mean daily animal protein intake was 9.6 E% and 0.68 g/kg body weight. Baseline characteristics per quartile of total protein intake are provided in Supplementary Table 1.

3.1. Associations of protein intake with body fat mass and distribution

In the total study population, a higher total protein intake was significantly associated with an increased BMI (mean difference [95 % confidence interval (CI)]: 0.86 kg/m² [0.01,1.71] per 5 E% increase of protein intake, Table 2), FMI (1.33[0.67, 1.99]), body fat percentage (4.54[2.76, 6.31]), gynoid fat percentage (3.63[1.86, 5.39]), and android fat percentage (3.12[0.70, 5.54]). After splitting total protein into animal and plant-sourced protein, most of these associations seemed to be driven by animal protein rather than plant protein (Table 2). We also found that the estimated associations of protein intake with fat mass and distribution were similar in men and women (Table 2).

3.2. Associations of protein intake with FFMI, handgrip strength, sarcopenia, and sarcopenic obesity risk score

In our study population, total or animal protein intake were not significantly associated with FFMI (−0.30[−0.73, 0.13] for total protein, Table 2). However, plant protein intake showed a negative association with FFMI (−0.96 [−1.89, −0.03]). Protein intake was not significantly associated with HGS (−1.51 [−3.63, 0.63]), but higher protein intake was associated with a lower sarcopenia risk (odds ratio [95 % CI]: 0.62 [0.43, 0.90] per 5E%). However, higher protein intake was also associated with a lower sarcopenic obesity index (mean difference [95 % CI]: −0.85[−1.5, −0.2]), indicating a higher risk of sarcopenic obesity. These associations were mainly driven by animal protein rather than plant protein. After stratifying by sex, we found that the estimated effect of protein intake on FFMI, HGS, sarcopenia, and sarcopenic obesity index were similar in men and women (Table 2).

3.3. Additional analyses

After additional adjustment for prevalent hypertension, dyslipidemia, and diabetes at baseline, estimates generally remained similar (Supplementary Table 2). When we removed participants with comorbidities at baseline, effect sizes remained similar and all associations between total protein and FMI, body fat percentage, gynoid fat percentage and sarcopenic obesity index remained statistically significant (Supplementary Tables 3 and 4). Second, interaction terms of protein intake with physical activity were non-significant (all p -values>0.1), suggesting that the effect of protein on outcomes does not differ in individuals with different physical activity levels. When adding fatty acid subgroups (i.e., SFA, MUFA, PUFA, trans-fat) in the statistical models instead of total fat, the estimated effects became stronger, and confidence intervals became narrower (Supplementary Tables 5 and 6). While adding carbohydrates in the models instead of total fat resulted in somewhat weaker estimates and larger confidence intervals (Supplementary Tables 7 and 8). In these analyses, the association between protein intake with FMI, fat percentage and sarcopenic obesity index remained statistically significant (Supplementary Tables 7 and 8). Moreover, the interaction term between age at body composition measurement and protein intake revealed that the effect of total protein intake on FMI, body fat percentage, and gynoid fat percentage became weaker over time (Supplementary Table 9). In the FFQ-stratified sensitivity analysis, we compared results from RS1/RS3 (389-item FFQ) and RS2 (170-item FFQ) with the main pooled analysis. Of the seven outcomes that were statistically significant in the pooled analysis, four (fat mass index, body fat percentage, gynoid fat percentage, and sarcopenia) showed consistent effect estimate directions across both FFQ groups. In contrast, for three outcomes—BMI, android fat

Table 1
Baseline characteristics of study participants.

	Total population	Men	Women
n	4576	1999	2577
Rotterdam Study sub-cohorts (n, %)			
RS-I	1205 (26.3)	523 (26.2)	682 (26.5)
RS-II	1059 (23.1)	495 (24.8)	564 (21.9)
RS-III	2312 (50.5)	981 (49.1)	1331 (51.6)
Age (years, SD)	65.14 (10.85)	65.29 (10.75)	65.02 (10.93)
Energy intake (kcal/day)	2213 (677)	2420 (701)	2052(611)
Protein intake (E%)	15.69 (2.76)	15.37 (2.66)	15.93 (2.82)
Protein intake (g/kg BW)	1.13 (0.38)	1.09 (0.34)	1.16 (0.40)
Plant protein intake (E%)	6.06 (1.41)	6.02 (1.40)	6.10 (1.41)
Plant protein intake (g/kg BW)	0.45 (0.19)	0.44 (0.18)	0.45 (0.19)
Animal protein intake (E%)	9.64 (3.04)	9.37 (2.94)	9.85 (3.11)
Animal protein intake (g/kg)	0.68 (0.27)	0.65 (0.25)	0.70 (0.29)
Fat intake (E%)	33.63 (7.34)	33.84 (7.21)	33.47 (7.43)
Carbohydrate intake (E%)	44.14 (7.63)	43.43 (7.66)	44.69 (7.57)
Alcohol intake (E%)	4.08 (4.80)	5.17 (5.36)	3.24 (4.13)
Education (n, %)			
primary	366 (8.1)	127 (6.4)	239 (9.3)
Lower/intermediate general or lower vocational education	1763 (38.8)	498 (25.1)	1265 (49.5)
Intermediate vocational or higher general education	1364 (30.0)	739 (37.2)	625 (24.4)
Higher vocational education or university	1049 (23.1)	621 (31.3)	428 (16.7)
Smoking (n, %)			
Never smoker	1830 (40.1)	567 (28.5)	1263 (49.2)
Former smoker	2181 (47.8)	1206 (60.6)	975 (38.0)
Current smoker	547 (12.0)	216 (10.9)	331 (12.9)
Physical activity (MET-hours/week)	61.92 (52.73)	55.37 (52.00)	66.97 (52.75)
Dyslipidemia at baseline (n, %)	1836 (40.7)	754 (38.2)	1082 (42.6)
Hypertension at baseline (n, %)	2774 (60.8)	1277 (64.1)	1497 (58.3)
Diabetes at baseline (n, %)	477 (10.4)	249 (12.5)	228 (8.8)
Dietary guideline score (range 0–10)	6.76 (1.92)	6.40 (1.85)	7.05 (1.92)
Outcomes at the first measurement			
BMI (kg/m ²)	26.83 (3.38)	27.07 (3.07)	26.64 (3.59)
FMI (kg/m ²)	9.32 (2.87)	7.96 (2.33)	10.38 (2.81)
Android fat percentage	42.59 (8.85)	40.04 (8.37)	44.57 (8.70)
Gynoid fat percentage	37.47 (8.96)	29.91 (5.85)	43.35 (6.09)
Body fat percentage	34.22 (7.71)	28.96 (6.12)	38.30 (6.19)
FFMI (kg/m ²)	17.51 (2.06)	19.11 (1.64)	16.27 (1.40)
Hand grip strength(kg)	27.49 (10.11)	35.47 (8.89)	21.34 (5.77)
Sarcopenic obesity index	0.21 (2.21)	0.09 (2.29)	0.29 (2.14)
Sarcopenia (n, %)	88 (2.0)	52 (2.7)	36 (1.4)

RS= Rotterdam Study. MET*Hour/week = Hours of Metabolic equivalent of task per week, BMI=Body mass index. FMI=Fat mass index. FFMI=Fat free mass index. Continuous data are shown in mean with Standard deviations, and categorical variables are shown as the number of cases and percentage.

percentage, and the sarcopenic obesity index—the associations in the smaller RS2 sub-cohort were null or even in opposite direction, but with very wide confidence intervals in all case. These findings are presented in [Supplementary Table 10](#).

4. Discussion

In this longitudinal population-based study, we observed that higher habitual protein intake is associated with a higher BMI and that this association is driven by more fat mass, not muscle mass. Although no statistically significant associations were found between protein intake and muscle mass or strength, we observed that higher protein intake is associated with lower odds of having sarcopenia. However, we also observed that higher protein intake is associated with a higher sarcopenic obesity risk.

In the field of obesity, especially among the elderly, it is important to take into account the distribution of fat mass since fat mass accumulated at different places represents distinct health threats [15]. Studies have proven that particularly visceral adipose mass - and its proxies such as waist-to-hip ratio or waist circumference, is the most strongly associated with cardiometabolic risk factors [23]. However, measuring visceral adipose mass accurately is challenging without DXA, which is considered a golden standard for body composition measurement

[24]. DXA provides more precise measurements of adipose tissue quantity and allows for assessing its distribution. Our study found that higher protein intake is not only associated with higher FMI but also a higher fat percentage in the android region, indicative of visceral adipose mass.

Interestingly, our results from long-term follow-up in a population-based cohort showed different results than those from short-term interventions, which suggests that protein supplementation may result in lower body fat mass [25]. These discrepancies may be caused by other changes in diet and life-style following a short-term high-protein diet or supplementation, e.g., a lower energy intake because of increased satiety, which may not last in a long-term real-world setting with different food sources. Also, overall lower intake ranges of habitual protein intake as compared to high-protein interventions or interactions with exercise may play a role. Another explanation is that, in some of these clinical trials, the protein was supplemented as "pure" protein and not through protein from foods, where it is consumed mainly from meat, often not totally lean. In our study, we observed no differences in the associations of protein with body composition by different levels of physical activity. However, higher levels of physical activity or specific types, such as resistance training, may be needed to observe these potential modifications.

Table 2
Associations of protein intake with body composition measures and sarcopenia.

	Total population						Men						Women					
	Total protein		Animal protein		Plant protein		Total protein		Animal protein		Plant protein		Total protein		Animal protein		Plant protein	
	Linear mixed model ^a																	
	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P	Estimate (95%CI)	P
BMI	0.86 (0.01,1.71)	0.05	0.86 (0.01,1.71)	0.05	0.38 (−1.46,2.22)	0.69	0.76 (−0.46,1.98)	0.22	0.95 (−0.28,2.18)	0.13	−1.17 (−3.71,1.36)	0.36	1.17 (−0.01,2.35)	0.05	1.21 (0.02,2.39)	0.05	−0.23 (−2.78,2.32)	0.86
FMI	1.33 (0.67,1.99)	<0.001	1.32 (0.66,1.99)	<0.001	1.2 (−0.17,2.68)	0.09	1.08 (0.11,2.05)	0.03	1.26 (0.29,2.23)	0.01	0.07 (−1.92,2.07)	0.94	1.03 (0.11,1.95)	0.03	1.06 (0.14,1.99)	0.03	−0.12 (−2.11,1.88)	0.91
BF%	4.54 (2.76,6.31)	<0.001	4.52 (2.74,6.31)	<0.001	4.52 (0.69,8.36)	0.02	3.06 (0.63,5.48)	0.01	3.48 (1.03,5.93)	0.01	1.78 (−3.26,6.81)	0.49	2.83 (0.54,5.12)	0.02	2.94 (0.64,5.25)	0.01	−0.83 (−5.79,4.14)	0.75
GF%	3.63 (1.86,5.39)	<0.001	3.62 (1.85,5.39)	<0.001	3.44 (−0.38,7.25)	0.08	2.89 (0.27,5.51)	0.03	1.66 (−0.73,4.04)	0.17	6.17 (1.27,11.07)	0.01	1.3 (−0.82,3.41)	0.23	1.01 (−1.13,3.14)	0.36	4.22 (−0.4,8.83)	0.07
AF%	3.12 (0.7,5.54)	0.01	3.01 (0.59,5.44)	0.02	4.69 (−0.56,9.94)	0.08	1.43 (−2.22,5.08)	0.44	1.56 (−2.1,5.22)	0.40	1.5 (−6.04,9.03)	0.70	2.63 (−0.58,5.84)	0.11	2.62 (−0.61,5.86)	0.11	1.68 (−5.3,8.67)	0.64
FFMI	−0.3 (−0.73,0.13)	0.18	−0.28 (−0.71,0.15)	0.20	−0.96 (−1.89, −0.03)	0.04	−0.04 (−0.7,0.63)	0.92	0 (−0.67,0.67)	1.00	−1.11 (−2.48,0.27)	0.12	0.25 (−0.25,0.75)	0.33	0.26 (−0.24,0.76)	0.31	−0.31 (−1.39,0.77)	0.58
HGS	−1.51 (−3.63,0.62)	0.17	−1.56 (−3.69,0.58)	0.15	0.12 (−4.5,4.73)	0.96	−0.24 (−4.39,3.9)	0.91	−0.31 (−4.5,3.87)	0.88	1.53 (−7.12,10.17)	0.73	−0.48 (−2.59,1.63)	0.65	−0.49 (−2.61,1.62)	0.65	0.62 (−4.06,5.29)	0.80
SO index	−0.85(−1.5,−0.2)	0.01	−0.92(−1.58,−0.26)	0.01	0.12 (−1.32,1.55)	0.87	−0.25 (−1.22,0.73)	0.62	−0.3 (−1.28,0.68)	0.54	0.92 (−1.12,2.97)	0.37	−0.84 (−1.7,0.02)	0.05	−0.85 (−1.71,0.01)	0.05	0.13 (−1.77,2.02)	0.89
	GEE model ^b																	
	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P	OR (95%CI)	P
Sarcopenia	0.62 (0.43,0.90)	0.01	0.62 (0.43,0.90)	0.01	0.57 (0.21,1.54)	0.27	0.60 (0.39,0.93)	0.02	0.597 (0.38,0.93)	0.02	0.67 (0.21,2.17)	0.50	0.65 (0.34,1.27)	0.21	0.66 (0.35,1.27)	0.21	0.30 (0.04,2.28)	0.25

For BMI, FMI, BF%, GF%, AF%, and FFMI, 4576 participants were included in the analysis, with 1999 men and 2577 women. For HGS, SO index, and Sarcopenia, 4471 participants were included in the analysis, with 1946 men and 2525 women.

The multivariable nutrition density substitution model was utilized for all statistical models to account for intake of energy and macronutrients other than protein. This involved including total energy intake (kcal/day), as well as dietary protein, fat, and alcohol intake as percentages of total energy intake (E%) (all included per 5E%). By not including dietary carbohydrate intake, the effect estimates of dietary protein intake can be interpreted as the mean difference in outcome measures per 5E% increase in protein intake at the expense of carbohydrate intake while keeping total energy intake constant. Age at measurement, sex, sub-cohort, physical activity, smoking, alcohol, level of education, and diet quality were adjusted in all models (model 1).

BMI=Body mass index. FMI=Fat mass index. FFMI=Fat free mass index. GF% = Gynoid fat percentage. AF% = Android fat percentage. BF% = Body fat percentage. HGS=Hand grip strength. SO=Sarcopenic obesity.

^a Effect estimates are the mean difference and 95 %-confidence intervals (95%CI) derived from linear mixed models. Linear mixed models were built with random intercepts and slopes (age at the time of measurement), including a two-way interaction term between age at each follow-up and protein intake and in our models.

^b Effect estimates are odds ratio (OR) and 95 %-confidence intervals (95%CI) derived from logistic regression models using generalized estimating equation (GEE) models.

The mechanism linking higher protein intake, especially from animal sources, to fat-related outcomes is not fully understood. One hypothesis suggests that animal protein may be associated with increased fat mass or adiposity through insulin-related pathways. In particular, branched-chain amino acids (BCAAs), which are abundant in animal protein, may impair insulin signaling through several mechanisms. First, BCAAs can activate the mTOR–S6K pathway, leading to insulin receptor substrate inhibition and reduced insulin sensitivity [26]. Second, BCAA metabolites such as 3-hydroxyisobutyrate (3-HIB) have been associated with insulin resistance in both animal and human studies [27,28]. Third, experimental studies have shown that BCAAs may induce metabolic stress in pancreatic islet β cells, further impairing insulin function [29].

The elderly population, with on average low lean mass and low muscle strength, is at higher risk of disability, frailty, and fractures [30,31]. The current study did not find a significant association between protein intake and measures of fat-free mass. This is not in line with a previous meta-analysis that used data from RCTs, which found a positive dose–response between protein intake and lean body mass, with or without resistance training [32]. A possible explanation is that this RCT-based meta-analysis studied high-protein diets and intervention times ranging from 0.5 to 18 months, which may not translate to long-term effects of variations in generally lower intake levels of habitual protein. Our results do align with another long-term observational study, in which higher total, animal, or vegetable protein intake was not associated with a 5-year change in mid-thigh muscle CSA in older adults ($n = 1561$) [33]. Yet, in another 2-year observational study, protein intake was associated with 3-year changes in lean mass ($n = 2066$) [34].

We found no association between protein intake and HGS. Previous reports on protein with HGS are contradictory. A recent meta-analysis of 16 RCTs also found no significant effect of total protein on HGS [9]. Similarly, a systematic review of 14 RCTs on dairy protein observed a significant increase in appendicular muscle mass, but no effect on HGS [35]. In line with this, another systematic review, which included 74 RCTs, reported increasing protein could result in higher lean body mass but that the effects on HGS were inconclusive [36]. However, a meta-analysis of 22 cross-sectional cohorts observed that a higher protein intake exceeding the recommended dietary allowance was associated with higher HGS [37]. This observation was further supported by a longitudinal cohort study that followed 1896 older adults for 14 years and found that animal protein, not plant protein, was associated with preserving HGS [38]. Although we did not observe significant associations with lean mass or handgrip strength, this may reflect a ceiling effect, as average protein intake in our population exceeded current dietary recommendations. Further studies are needed to determine whether additional protein intake provides measurable benefits in populations with already adequate intake.

In the current study, we did observe that higher protein intake may have a protective effect on sarcopenia risk. This observation is consistent with a recent systematic review and meta-analysis ($n = 3353$, average age = 73), which found that elderly with sarcopenia consumed less protein than non-sarcopenic individuals [36]. The apparent inconsistency in our null findings for muscle mass and strength on one hand and lower risk for sarcopenia on the other hand may be explained by several factors. First, these findings suggest that protein intake may only affect more extreme levels of low muscle mass and function, as reflected in the clinical sarcopenia definition, but that this effect is not present or not large enough to detect in a normal range of muscle mass and function, considering the low prevalence of sarcopenia in the Rotterdam Study. Second, inconsistencies within our study and with other

studies might be explained by the diversity in physical activity levels and types. Previous research emphasized the synergy of dietary protein and physical activity, particularly through resistance or high-intensity exercises, in promoting muscle mass and function [39]. However, only one-fourth of our study population still participated in vigorous physical activity and only at very low levels. Finally, our population-based cohort among middle-aged and elderly presents a significant prevalence of various comorbidities and disease risk factors. Individuals with such conditions may exhibit diverse dietary and altered physical activity habits, while these diseases may also influence body composition [40,41].

In the current study, we also evaluated sarcopenic obesity risk using a novel continuous sarcopenic obesity index (Benz et al., in progress), as the number of cases of sarcopenic obesity according to clinical criteria in our population is too low to run analyses. This sarcopenic obesity index incorporates HGS, ALM/W, and BF% as the recommended indicators by ESPEN/EASO Consensus [6], but as continuous variables rather than with cut-offs. Our results suggest that higher animal protein intake increases the risk of sarcopenic obesity. In light of our findings for the other outcomes, this increased risk might be driven by the association with higher body fat. However, sensitivity analyses show that the association with the sarcopenic obesity index was primarily driven by RS1 and RS3, which used the 389-item FFQ, and was not observed in RS2, which used the 170-item FFQ.

The food source of protein also matters. Our results show that most associations with higher FMI, fat percent in the android region, and sarcopenic obesity risk are driven by animal protein, not plant protein. These effects may be more pronounced for animal proteins, which have higher digestibility and greater concentrations of essential amino acids and BCAAs than plant proteins, leading to stronger anabolic stimulation but also greater potential to disrupt insulin sensitivity. This suggests that plant protein may be a more favorable choice to prevent or reduce obesity. This observation is in line with a previous RCT among 2413 adult European participants in which they found that the risk of overweight or obesity is reduced if plant protein replaces animal protein [42]. However, we also observed that plant protein is associated with a lower FFMI and we found no protective association between plant protein and sarcopenia. This might be explained by differences in protein quality, e.g. proteins from animal foods usually have complete EAA profiles, crucial for muscle protein synthesis [8] and have higher bioavailability [43]. Future studies should focus on optimal protein combinations from plant sources and plant-based dietary patterns for muscle mass and functioning.

4.1. Strengths and limitation

Our study has several strengths. Firstly, although we cannot establish a causal relationship between protein and outcomes, the prospective design with a large sample size provides more insights into their longitudinal associations in a real-world setting. Secondly, the body composition outcomes are objectively measured using DXA, with increased accuracy as compared to anthropometric proxies. Furthermore, The average protein intake in our study population was 1.13 g/kg/day, accounting for 15.7 % of total energy intake and exceeding the recommended 0.8 g/kg/day. This level is consistent with that observed in other Western cohorts [22], supporting the generalizability of our findings and reducing concerns about selection bias. Lastly, several additional analyses were conducted to explore potential effect modification, different macronutrient substitution effects, and the role of many confounders, which overall supported the robustness of the results. However, results should also be interpreted with caution due to

several limitations. Firstly, dietary intake was self-reported, for which measurement errors are unavoidable. Yet, the FFQs we used have been previously validated and showed good reliability in ranking participants according to their nutrient intake, specifically protein intake. Secondly, we only used data on protein intake at baseline and could not consider potential changes in dietary intake over time, such as reduced intake due to aging or the development of chronic disease, which may lead to misclassification of long-term exposure and could bias the observed associations. Furthermore, this study contains three sub-cohorts of the RS. Although we adjusted for cohort and other potential confounders in the analysis, and each cohort used standardized protocols, some residual heterogeneity may remain. At the same time, the inclusion of multiple cohorts provides a larger sample size, which improves power and helps to mitigate random variation. Although we used nutrient density models to account for other macronutrients and adjusted for an overall dietary quality score to control for broader diet quality, we cannot fully exclude residual confounding from other dietary factors that may still partially explain the observed associations. Lastly, the Rotterdam Study is a predominantly ethnically non-diverse population cohort, so the result may not be directly generalized to other populations.

5. Conclusion

In this longitudinal cohort study, we observed that higher animal protein is associated with lower sarcopenia risk, but also with more obesity over time. In contrast, plant protein was not associated with sarcopenia or obesity. Our results provide evidence of the role of diet protein in sarcopenia and obesity in the general elderly population. Future studies should focus on identifying a protein-balanced diet to maintain muscle while preventing obesity and on more personalized dietary recommendations for the elderly based on their current body composition and health status.

Consent to publish

Not Applicable. The current study did not contain identifiable individual data.

Author contributions

All authors contributed to the study's conception and design. Analysis was performed by Yahong Wu. Tables and figures were made by Yahong Wu. The first draft of the manuscript was written by Yahong Wu, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Joyce B.J. van Meurs, Cindy G. Boer, and Trudy Voortman designed the study and supervised this work. Trudy Voortman had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Ethics approval and consent to participate

The Rotterdam Study has been approved by the Medical Ethics Committee of Erasmus MC (registration number MEC 02.1015) and by the Dutch Ministry of Health, Welfare, and Sport (Population Screening Act WBO, license number 1071272-159521-PG). Written informed consent was obtained from all participants.

Data sharing statement

Data are available upon reasonable request. All relevant data supporting the key findings of this study are available within the

article and its supplementary data. Due to ethical and legal restrictions (GDPR), individual-level data from the Rotterdam Study cannot be made publicly available. Data are available upon request to the data manager of the Rotterdam Study, Frank van Rooij (f.vanrooij@erasmusmc.nl), and are subject to local rules and regulations. This includes submitting a proposal to the management team of RS, where upon approval, analysis needs to be done on a local server with protected access, complying with GDPR.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT, 2024, in order to check grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.clnu.2025.07.033>.

References

- [1] Zoico E, Di Francesco V, Mazzali G, Vettor R, Fantin F, Bissoli L, et al. Adipocytokines, fat distribution, and insulin resistance in elderly men and women. *J Gerontol A Biol Sci Med Sci* 2004;59(9):M935–9.
- [2] Bjorntorp P. Metabolic implications of body fat distribution. *Diabetes Care* 1991;14(12):1132–43.
- [3] Yeung SSY, Reijnierse EM, Pham VK, Trappenburg MC, Lim WK, Meskers CGM, et al. Sarcopenia and its association with falls and fractures in older adults: a systematic review and meta-analysis. *J Cachexia Sarcopenia Muscle* 2019;10(3):485–500.
- [4] Veronese N, Koyanagi A, Cereda E, Maggi S, Barbagallo M, Dominguez LJ, et al. Sarcopenia reduces quality of life in the long-term: longitudinal analyses from the English longitudinal study of ageing. *Eur Geriatr Med* 2022;13(3):633–9.
- [5] Gortan Cappellari G, Guillet C, Poggigalle E, Ballesteros Pomar MD, Batsis JA, Boirie Y, et al. Sarcopenic obesity research perspectives outlined by the sarcopenic obesity global leadership initiative (SOGLI) – proceedings from the SOGLI consortium meeting in rome November 2022. *Clin Nutr* 2023;42(5):687–99.
- [6] Donini LM, Busetto L, Bischoff SC, Cederholm T, Ballesteros-Pomar MD, Batsis JA, et al. Definition and diagnostic criteria for sarcopenic obesity: ESPEN and EASO consensus statement. *Obes Facts* 2022;15(3):321–35.
- [7] Eglseer D, Traxler M, Schoufour JD, Weijs PJM, Voortman T, Boirie Y, et al. Nutritional and exercise interventions in individuals with sarcopenic obesity around retirement age: a systematic review and meta-analysis. *Nutr Rev* 2023;81(9):1077–90.
- [8] Boirie Y. Physiopathological mechanism of sarcopenia. *J Nutr Health Aging* 2009;13(8):717–23.
- [9] Lim MT, Pan BJ, Toh DWK, Sutanto CN, Kim JE. Animal protein versus plant protein in supporting lean mass and muscle strength: a systematic review and meta-analysis of randomized controlled trials. *Nutrients* 2021;13(2).
- [10] Moon J, Koh G. Clinical evidence and mechanisms of high-protein diet-induced weight loss. *J Obes Metab Syndr* 2020;29(3):166–73.
- [11] Zhao H, Song A, Zheng C, Wang M, Song G. Effects of plant protein and animal protein on lipid profile, body weight and body mass index on patients with hypercholesterolemia: a systematic review and meta-analysis. *Acta Diabetol* 2020;57(10):1169–80.
- [12] Badely M, Sepandi M, Samadi M, Parastouei K, Taghdir M. The effect of whey protein on the components of metabolic syndrome in overweight and obese individuals: a systematic review and meta-analysis. *Diabetes Metabol Syndr* 2019;13(6):3121–31.
- [13] Westterp-Plantenga MS, Nieuwenhuizen A, Tome D, Soenen S, Westterp KR. Dietary protein, weight loss, and weight maintenance. *Annu Rev Nutr* 2009;29:21–41.
- [14] Ellinger S, Amini AM, Haardt J, Lehmann A, Schmidt A, Bischoff-Ferrari HA, et al. Protein intake and body weight, fat mass and waist circumference: an umbrella review of systematic reviews for the evidence-based guideline on protein intake of the German Nutrition Society. *Eur J Nutr* 2024;63(1):3–32.
- [15] Chait A, den Hartigh LJ. Adipose tissue distribution, inflammation and its metabolic consequences, including diabetes and cardiovascular disease. *Front Cardiovasc Med* 2020;7:22.
- [16] Ikram MA, Kieboom BCT, Brouwer WP, Brusselle G, Chaker L, Ghanbari M, et al. The Rotterdam Study. Design update and major findings between 2020 and 2024. *Eur J Epidemiol* 2024;39:183–206.
- [17] Goldbohm RA, van den Brandt PA, Brants HA, van't Veer P, Al M, Sturmans F, et al. Validation of a dietary questionnaire used in a large-scale prospective cohort study on diet and cancer. *Eur J Clin Nutr* 1994;48(4):253–65.
- [18] Feunekes GI, Van Staveren WA, De Vries JH, Burema J, Hautvast JG. Relative and biomarker-based validity of a food-frequency questionnaire estimating intake of fats and cholesterol. *Am J Clin Nutr* 1993;58(4):489–96.
- [19] Klipstein-Grobusch K, den Breeijen JH, Goldbohm RA, Geleijnse JM, Hofman A, Grobbee DE, et al. Dietary assessment in the elderly: validation of a semi-quantitative food frequency questionnaire. *Eur J Clin Nutr* 1998;52(8):588–96.
- [20] Cruz-Jentoft AJ, Bahat G, Bauer J, Boirie Y, Bruyere O, Cederholm T, et al. Sarcopenia: revised European consensus on definition and diagnosis. *Age Ageing* 2019;48(1):16–31.
- [21] Voortman T, Kieffe-de Jong JC, Ikram MA, Stricker BH, van Rooij FJA, Lahousse L, et al. Adherence to the 2015 Dutch dietary guidelines and risk of non-communicable diseases and mortality in the Rotterdam Study. *Eur J Epidemiol* 2017;32(11):993–1005.
- [22] Mendonca NMP, Hengeveld LM, Presse N, Canhao H, Simonsick E, Kritchevsky SB, et al. Protein intake, physical activity and grip strength in European and North American community-dwelling older adults: a pooled analysis of individual participant data from four longitudinal ageing cohorts. *Br J Nutr* 2023;129(7):1221–31.
- [23] Elffers TW, de Mutsert R, Lamb HJ, de Roos A, Willems van Dijk K, Rosendaal FR, et al. Body fat distribution, in particular visceral fat, is associated with cardiometabolic risk factors in obese women. *PLoS One* 2017;12(9):e0185403.
- [24] Shepherd JA, Ng BK, Sommer MJ, Heymsfield SB. Body composition by DXA. *Bone* 2017;104:101–5.
- [25] Li M, Liu F. Effect of whey protein supplementation during resistance training sessions on body mass and muscular strength: a meta-analysis. *Food Funct* 2019;10(5):2766–73.
- [26] Tremblay F, Krebs M, Dombrowski L, Brehm A, Bernroider E, Roth E, et al. Overactivation of S6 kinase 1 as a cause of human insulin resistance during increased amino acid availability. *Diabetes* 2005;54(9):2674–84.
- [27] Haufe S, Engeli S, Kaminski J, Witt H, Rein D, Kamlage B, et al. Branched-chain amino acid catabolism rather than amino acids plasma concentrations is associated with diet-induced changes in insulin resistance in overweight to obese individuals. *Nutr Metabol Cardiovasc Dis* 2017;27(10):858–64.
- [28] Jang C, Oh SF, Wada S, Rowe GC, Liu L, Chan MC, et al. A branched-chain amino acid metabolite drives vascular fatty acid transport and causes insulin resistance. *Nat Med* 2016;22(4):421–6.
- [29] Fontana L, Cummings NE, Arriola Apelo SI, Neuman JC, Kasza I, Schmidt BA, et al. Decreased consumption of branched-chain amino acids improves metabolic health. *Cell Rep* 2016;16(2):520–30.
- [30] Xue QL, Walston JD, Fried LP, Beamer BA. Prediction of risk of falling, physical disability, and frailty by rate of decline in grip strength: the women's health and aging study. *Arch Intern Med* 2011;171(12):1119–21.
- [31] Marsh AP, Rejeski WJ, Espeland MA, Miller ME, Church TS, Fielding RA, et al. Muscle strength and BMI as predictors of major mobility disability in the Lifestyle Interventions and Independence for Elders pilot (LIFE-P). *J Gerontol A Biol Sci Med Sci* 2011;66(12):1376–83.
- [32] Tagawa R, Watanabe D, Ito K, Ueda K, Nakayama K, Sanbongi C, et al. Dose-response relationship between protein intake and muscle mass increase: a systematic review and meta-analysis of randomized controlled trials. *Nutr Rev* 2020;79(1):66–75.
- [33] Verreijen AM, Engberink MF, Houston DK, Brouwer IA, Cawthon PM, Newman AB, et al. Dietary protein intake is not associated with 5-y change in mid-thigh muscle cross-sectional area by computed tomography in older adults: the Health, Aging, and Body Composition (Health ABC) Study. *Am J Clin Nutr* 2019;109(3):535–43.
- [34] Houston DK, Nicklas BJ, Ding J, Harris TB, Tyllavsky FA, Newman AB, et al. Dietary protein intake is associated with lean mass change in older, community-dwelling adults: the Health, Aging, and Body Composition (Health ABC) Study. *Am J Clin Nutr* 2008;87(1):150–5.
- [35] Hanach NI, McCullough F, Avery A. The impact of dairy protein intake on muscle mass, muscle strength, and physical performance in middle-aged to older adults with or without existing sarcopenia: a systematic review and meta-analysis. *Adv Nutr* 2019;10(1):59–69.
- [36] Nunes EA, Colenso-Semple L, McKellar SR, Yau T, Ali MU, Fitzpatrick-Lewis D, et al. Systematic review and meta-analysis of protein intake to support muscle mass and function in healthy adults. *J Cachexia Sarcopenia Muscle* 2022;13(2):795–810.
- [37] Coelho-Junior HJ, Calvani R, Tosato M, Landi F, Picca A, Marzetti E. Protein intake and physical function in older adults: a systematic review and meta-analysis. *Ageing Res Rev* 2022;81:101731.
- [38] Yuan M, Pickering RT, Bradlee ML, Mustafa J, Singer MR, Moore LL. Animal protein intake reduces risk of functional impairment and strength loss in older adults. *Clin Nutr* 2021;40(3):919–27.
- [39] O'Bryan KR, Doering TM, Morton RW, Coffey VG, Phillips SM, Cox GR. Do multi-ingredient protein supplements augment resistance training-induced gains in skeletal muscle mass and strength? A systematic review and meta-analysis of 35 trials. *Br J Sports Med* 2020;54(10):573–81.
- [40] Juez LD, Priego P, Bajawi M, Cuadrado M, Blazquez LA, Sanchez-Picot S, et al. Impact of sarcopenic obesity on long-term cancer outcomes and post-operative complications after gastrectomy for gastric cancer. *J Gastrointest Surg* 2023;27(1):35–46.
- [41] Rock CL, Thomson C, Gansler T, Gapstur SM, McCullough ML, Patel AV, et al. American cancer society guideline for diet and physical activity for cancer prevention. *CA Cancer J Clin* 2020;70(4):245–71.
- [42] Navas-Carretero S, San-Cristobal R, Livingstone KM, Celis-Morales C, Marsaux CF, Macready AL, et al. Higher vegetable protein consumption, assessed by an isoenergetic macronutrient exchange model, is associated with a lower presence of overweight and obesity in the web-based Food4me European study. *Int J Food Sci Nutr* 2019;70(2):240–53.
- [43] Berrazaga I, Micard V, Gueugneau M, Walrand S. The role of the anabolic properties of Plant- versus animal-based protein sources in supporting muscle mass maintenance: a critical review. *Nutrients* 2019;11(8).