The Journal of Frailty & Aging 14 (2025) 100004

Contents lists available at ScienceDirect

The Journal of Frailty & Aging

journal homepage: www.elsevier.com/locate/tjfa

Original Research

High dietary acid load increases the risk of disability in women aged 75 years and older: A community-based cohort study

Kaori Kinoshita[a,*], Yosuke Osuka[a], Kazuhiro Yoshiura[a], Noriko Hori[a], von Fingerhut Georg[a], Shosuke Satake[a,b], Hidenori Arai[c]

[a] Department of Frailty Research, Center for Gerontology and Social Science, Research Institute, National Center for Geriatrics and Gerontology, Obu, Aichi, Japan
[b] Department of Geriatric Medicine, Hospital, National Center for Geriatrics and Gerontology, Obu, Aichi, Japan
[c] National Center for Geriatrics and Gerontology, Obu, Aichi, Japan

ARTICLE INFO

Keywords:
Asian
Older adults
Epidemiology
Functional decline
Feeding behavior

ABSTRACT

Background: Metabolic acidosis caused by acidogenic diets increases muscle catabolism. High acidogenic diets can increase muscle loss in older adults; however, their association with functional outcomes remains unclear.
Objectives: To investigate whether high acidogenic diets increase the incidence of disability.
Design: Longitudinal study.
Setting: Community-based.
Participants: We included 1,704 community-dwelling Japanese individuals aged ≥ 75 years without disabilities at baseline (52.2 % females).
Measurements: Baseline dietary acid load was assessed using potential renal acid load (PRAL) values, which reflect urinary acidity—with higher values indicating more acidogenic diets. The outcome measure was the one-year incidence of disability, defined as needing for long-term care or support based on certification by the Japanese long-term care insurance system. As the effects of PRAL are reportedly sex-specific, separate analyses were conducted for males and females. The participants were categorized into tertiles (T1–T3, with T1 as the reference) based on their PRAL values. Odds ratios (ORs) and 95 % confidence intervals (CIs) for outcome were calculated using multiple logistic regression analysis after adjusting for age, body mass index, living status, smoking status, hypertension, diabetes, dyslipidemia, energy intake, and alcohol intake.
Results: The PRAL ranges in groups T1, T2, and T3 were: −64.51 to 0.21, 0.27 to 11.34, and 11.41 to 61.00, respectively, in males, and −61.22 to −3.84, −3.75 to 5.89, and 5.90 to 38.68, respectively, in females. Disabilities occurred in 44 (5.7 %) males and 71 (8.7 %) females. ORs (95 % CIs) for disability in T2 and T3 were 0.79 (0.35–1.76) and 0.81 (0.37–1.79), respectively, in males and 1.10 (0.57–2.13) and 1.96 (1.06–3.61), respectively, in females.
Conclusions: A high dietary acid load increased the incidence of disability in older females. Therefore, managing an acidogenic diet may help maintain daily living functions in older females. Future studies should investigate whether sex is an effect modifier.

1. Introduction

By 2050, the number of older adults who need assistance with their activities of daily living is predicted to increase four-fold [1]. Therefore, addressing the care needs of older adults has become a public health priority worldwide. Maintaining muscle health is important for preventing declines in physical function and disability. Nutritional intake represents a key modifiable lifestyle factor that is necessary for maintaining proper muscle function. Certain nutrients may play a key role in maintaining muscle function, such as protein, vitamin D, and antioxidants [2–4]. However, recently, the focus in the field of nutrition has shifted from single nutrients to overall dietary features [5]. This is because individual nutrients are not consumed in isolation, and different nutrients interact with each other during various metabolic processes [6,7]. As diets are frequently influenced by ethnicity and culture, examining them in terms of nutrient composition may be more useful when applying research findings to the diets of different ethnic groups.

The potential renal acid load (PRAL) is one of the values defined by the combination of several nutrients in the diet [8]. This parameter indicates the acid- or base-producing capacity of the diet. It is calculated based on the acidic (protein and phosphorus) and alkaline (calcium, potassium, and magnesium) nutrients in the diet [8,9]. PRAL reflects urine acidity, with higher values indicating a more acidogenic diet [8,10]. Thus, proteins that are important for maintaining physical func-

* Corresponding author.
E-mail address: kino4ta@ncgg.go.jp (K. Kinoshita).

https://doi.org/10.1016/j.tjfa.2024.100004
Received 29 July 2024; Accepted 13 November 2024
Available online 1 January 2025

tion exert acidogenic effects. In contrast, calcium, potassium, and magnesium are abundant in vegetables and fruits. An acidic diet could lead to skeletal muscle protein catabolism, whereas the intake of alkalinizing compounds has been reported to increase muscle strength [2].

In acute metabolic acidosis, muscle protein breakdown is accelerated, and muscle synthesis is suppressed, leading to progressive muscle catabolism [11]. The amino acids released by this skeletal muscle catabolism cause protons (H^+) to be excreted as ammonium ions, which relieves acidosis. Therefore, skeletal muscle catabolism is considered an adaptive response to metabolic acidosis [12–14]. Muscle catabolism, caused by metabolic acidosis, occurs during starvation, trauma, sepsis, burns, and chronic renal failure. However, muscle catabolism can also occur because of age-related reduction in the urinary excretion of H^+ and acidogenic diets (i.e., diets with high PRAL values) [15]. Recently, several studies have reported that chronic diet-induced acidosis is associated with poor musculoskeletal health [9,15–22]. In older adults, diets with high PRAL levels may accelerate the decline in physical function and hasten the occurrence of disabilities related to activities of daily living. However, to the best of our knowledge, the association between dietary acid load and disability has not been reported. Therefore, we hypothesized that an acidogenic diet is likely to cause disability and aimed to investigate the association between dietary acid load and disability in community-dwelling older adults.

2. Methods

2.1. Study design and participants

This study was conducted among community-dwelling older adults aged ≥ 75 years who were living in Higashiura Town, Aichi, Japan, as of April 1, 2021. Higashiura is located in the center of Japan, has a total area of 31.14 km^2, and is home to approximately 50,000 people living in 21,000 households [23].

This study used health checkup and postal survey records as the baseline data. The local government conducted health checkups between June and August of 2021. In accordance with the Japanese medical system, this health checkup is conducted nationwide for older people aged ≥ 75 years. Health conditions, medical histories, blood test results, physical measurements, and health-related information (including smoking status) were all assessed by physicians and stored in the local government's database. In November 2021, a postal survey was conducted among all self-reliant citizens (including individuals who needed support for daily living based on the Japanese long-term care insurance system, further details of which are provided below) of Higashiura aged ≥ 75 years (n = 4,970 respondents). The questionnaire included a dietary assessment (further details of which are provided below) and household information, such as whether each participant lived alone. Thus, baseline data was collected between June and November 2021. Incidence rates of long-term care or support needs and deaths for all Higashiura citizens were also recorded in the local government's database. As of March 2023, the new certification of needing long-term care or support status that occurred after the baseline survey was used as outcome data.

This study employed an opt-out consent procedure, where potential participants were informed about the study through our official website. Participants were informed that their participation was voluntary and that they could decline to participate by email or telephone contact. This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Human Research of the National Center for Geriatrics and Gerontology, Japan (Approval no. 1532-2).

2.2. Outcome measure

The outcome measure was the incidence of new disability during the 1-year follow-up period. Disability was defined as a case where there was a need for care or support in daily living. These statuses were certificated based on the Japanese long-term care insurance system [24]. In the system, the Certification Committee of Needed Long-Term Care, comprising health, social care, and medical experts, decides how much care is needed based on the assessment results by the local authority and the physician's opinion [24]. The need for care is rated from level 1 to 5, and the need for support is rated from 1 to 2 [24]. Individuals who need long-term care are those who need help to live on a day-to-day basis, and individuals who need support are those who are basically able to live on their own but need help with certain aspects of their daily lives, such as cleaning, laundry, bathing, and cooking.

2.3. Assessment of dietary intake

For the baseline postal survey, the Brief Self-administered Diet History Questionnaire (BDHQ) was used to characterize habitual dietary intake [25]. Given the differences in food culture and dietary habits between countries, it is important to select appropriate questionnaires for each region. The BDHQ is commonly used to assess dietary habits in Japan, and its validity has been demonstrated in both young and older Japanese adults [25,26]. In its development, foods and beverages were specifically selected from those that are most commonly consumed in Japan, based on data from the National Health and Nutrition Survey of Japan [27]. The portion sizes for the selected items were derived from various recipe books for Japanese dishes [28,29].

The time required to complete the BDHQ is 15–20 min. Participants reported how frequently they had consumed selected foods and beverages during the previous month, following the instructions on the form. If participants were unable to complete the questionnaire themselves, a family member could complete it on their behalf. A BDHQ developer (EBNJAPAN, Tokyo, Japan) estimated nutrient intakes from the participants' responses based on the Standard Tables of Food Composition in Japan [30]. Similar to a previous study that also used the BDHQ [31], the total daily intake of each nutrient was adjusted for energy intake and normalized for each respondent based on their sex- and age-specific estimated energy requirements for moderate physical activity, according to the Dietary Reference Intakes for Japanese [32].

2.4. Assessment of dietary acid load

Dietary acid load was assessed using the PRAL value, which has been shown to reflect actual measurements of urinary acid excretion by Remer and Manz [8,10]. The value was calculated from the daily nutrient intake using the following formula:

$$PRAL\left(\frac{mEq}{day}\right) = \left(0.4888 \times \text{protein intake}\left(\frac{\text{g}}{\text{day}}\right)\right) + \left(0.0366 \times phosphorus\left(\frac{mg}{day}\right)\right) - \left(0.0205 \times potassium\left(\frac{mg}{day}\right)\right) - \left(0.0125 \times calcium\left(\frac{mg}{day}\right)\right) - \left(0.0263 \times magnesium\left(\frac{mg}{day}\right)\right)$$

A positive PRAL value indicates an acid-forming diet, while a negative one indicates a base-forming (or alkaline-forming) diet. After the digestion and absorption of food, acids or bases are produced as a result of various metabolic processes. The PRAL value shows the balance between acid- and base-forming diets. Acid-forming foods produce more acids than bases, while base-forming foods produce more bases than acids.

Dietary acid load can be assessed using the Net Endogenous Acid Production (NEAP) or the PRAL. To accurately measure NEAP, renal net acid excretion is measured using biochemical analysis of urine [33]. Remer and Manz [8,10] reported that PRAL is calculated based on 'dietary intake'. The objective of this study was to measure dietary acid

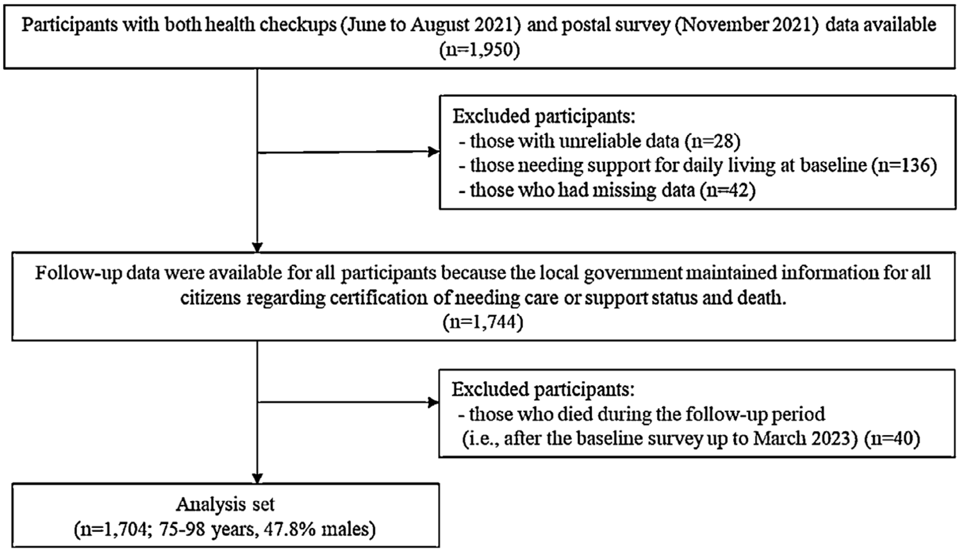

Fig. 1. Participant selection flowchart. This figure illustrates the flow of participant inclusion and exclusion for analysis in this study. This study used health checkup and postal survey records as the baseline data. The new certification of needing long-term care or support status as of March 2023, which occurred after the baseline survey, was used as outcome data. Incidence rates of long-term care or support needs and deaths for all of Higashiura citizens were recorded in the local government's database; thus, all of the participants could be followed. A total of 1,950 participants had both health checkup and postal survey data. Among them, 28 participants were excluded because their responses to the postal survey were considered unreliable. We also excluded participants who already had certification of needing support for daily living based on the Japanese long-term care insurance system at the baseline (*n* = 136), those with missing data (missing living status data, *n* = 39; and missing smoking status data, *n* = 3), and those who had died during the one-year follow-up period (*n* = 40). Finally, data from 1,704 participants were analyzed.

load based on dietary intake. Despite the availability of a formula for NEAP estimation using dietary intake, this formula only considers two nutrients: protein and potassium [33]. Hence, we employed the PRAL value in this study.

2.5. Covariates

Data regarding body mass index (BMI, kg/m^2; calculated from anthropometric data), medical histories of hypertension, diabetes, and dyslipidemia, and smoking status were obtained from health checkup data. Living status, energy intake (kcal/day), and alcohol intake (g/day) were obtained from the postal survey data. These covariates were determined based on previous studies [16,34,35].

2.6. Statistical analysis

Statistical analyses were conducted separately for males and females (defined based on biological sex), as sex-based differences have been reported regarding the physiological effects of PRAL values [17]. The participants were classified into three groups (T1, T2, and T3) based on sex-stratified tertiles of PRAL values. The T1 group had alkaline-forming diets, whereas the T3 group had acid-forming ones.

The characteristics of the participants between the PRAL groups were compared using a one-way analysis of variance and χ^2 test for continuous and categorical variables, respectively. Daily nutrients and food intake values were analyzed using the general linear model of the difference and trend among the three PRAL groups. Continuous variables are presented as means and standard deviations (SDs), whereas categorical ones are presented as numbers (n) and percentages (%).

Associations between the new occurrence of disability during the follow-up period and the PRAL group were analyzed using multiple logistic regression models. Odds ratios (ORs) and 95 % confidence intervals (CIs) for the incidence of disability were estimated using T1 as the reference group. Covariates included age; BMI (kg/m^2); energy intake (kcal/day); living status; smoking status; a medical history of hypertension, diabetes, and dyslipidemia (used as the number of comorbidities of these diseases, i.e., 0 to 3); and alcohol intake (g/day). These covariates were determined based on previous studies [16,34,35].

In the analysis, the participants with unreliable responses to the postal survey were excluded. An unreliable response was determined if the participants' dietary intake was estimated to be < 600 or >4,000 kcal/day based on a previous study [36].

All statistical analyses were performed using IBM SPSS Statistics for Windows, version 28.0 (IBM Corp., Armonk, N.Y., USA), and statistical significance was indicated by two-sided *P*-values of < 0.05.

3. Results

Data were available for both the postal survey and health checkups for 1,950 participants. Among them, 28 participants were excluded because their responses to the postal survey were considered unreliable. We also excluded participants who already had certification of needing support for daily living based on the Japanese long-term care insurance system at baseline (*n* = 136), those with missing data (missing living status data, *n* = 39; and missing smoking status data, *n* = 3), and those who died during the one-year follow-up period (*n* = 40). Eventually, data from 1,704 participants were analyzed (age range, 75–98 years; males, *n* = 814 [47.8 %], Fig. 1).

Table 1 shows the characteristics of the participants at baseline. There were no significant differences in age among the three PRAL groups for both males and females. For females, we detected a significant difference in BMI among T1, T2, and T3 for the PRAL groups (22.7 ± 3.3, 22.0 ± 3.2, and 23.1 ± 3.8, respectively, $P < 0.001$). For males, significant differences were observed in proportion (%) of participants living alone and hypertension among T1, T2, and T3 for the PRAL groups (living alone: 5.2, 6.6, and 10.7, respectively, P = 0.040; hypertension: 53.9, 50.4, and 69.4, respectively, $P < 0.001$). Tables 2 and 3 present the participants' nutritional intakes at baseline. The PRAL values for females in the T1 group ranged from −61.22 to −3.84, indicating that these participants consumed alkaline-forming diets, whereas those of males in T1 ranged from −61.5 to 0.21, thus including acid-forming diets. The protein intake per kg body weight significantly increased from the T1 to T3 group (P for group difference and trend were both < 0.001, for both males and females), and the animal protein ratio also significantly increased between these groups (P for group difference and trend were both < 0.001, for both males and females). In contrast, the intake of vegetables and fruits significantly decreased from the T1 to T3 group (P for group difference and trend were both < 0.001, for both males and females).

The multivariate-adjusted associations between the incidence of disability and the three PRAL groups are shown in Table 4. Disability occurred in 44 (5.7 %) males and 71 (8.7 %) females. Taking the T1 group as the reference, the adjusted ORs (95 % CIs) of the T1 and T2 PRAL groups for disability were 1.10 (0.57–2.13) and 1.96 (1.06–3.61), re-

Table 1
Characteristics of the study participants at baseline.

	PRAL groups in females* (*n* = 890)				PRAL groups in males* (*n* = 814)			
	T1 –61.22 to –3.84 (*n* = 296)	T2 –3.75 to 5.89 (*n* = 297)	T3 5.90 to 38.68 (n = 297)	P-value†	T1 –61.54 to 0.21 (*n* = 271)	T2 0.27 to 11.34 (*n* = 272)	T3 11.41 to 61.00 (*n* = 271)	P-value†
Age, years	80.1 ± 4.0	80.2 ± 3.6	79.8 ± 3.8	0.487	79.6 ± 3.8	79.9 ± 4.1	79.9 ± 3.6	0.536
BMI, kg/m^2	22.7 ± 3.3	22.0 ± 3.2	23.1 ± 3.8	<0.001	23.2 ± 2.8	23.0 ± 2.8	23.5 ± 2.8	0.056
EER, kcal/day	1,733.2 ± 265.8	1,652.3 ± 259.7	1,747.8 ± 299.3	<0.001	2,191.1 ± 291.5	2,125.4 ± 297.9	2,200.5 ± 307.6	0.006
Living alone	76 (25.7)	73 (24.6)	68 (22.9)	0.729	14 (5.2)	18 (6.6)	29 (10.7)	0.040
Current smoker	5 (1.7)	3 (1.0)	3 (1.0)	0.689	18 (6.6)	16 (5.9)	19 (7.0)	0.863
Hypertension	168 (56.8)	154 (51.9)	180 (60.6)	0.098	146 (53.9)	137 (50.4)	188 (69.4)	<0.001
Diabetes	32 (10.8)	27 (9.1)	31 (10.4)	0.766	51 (18.8)	40 (14.7)	37 (13.7)	0.218
Dyslipidemia	128 (43.2)	111 (37.4)	119 (40.1)	0.345	65 (24.0)	67 (24.6)	69 (25.5)	0.923
Albumin, g/dL	4.1 ± 0.2	4.1 ± 0.2	4.1 ± 0.2	0.192	4.1 ± 0.2	4.1 ± 0.3	4.1 ± 0.2	0.590
Triglycerides, mg/dL	111.3 ± 50.7	104.7 ± 51.2	109.5 ± 50.7	0.135	115.2 ± 57.9	120.1 ± 101.1	112.9 ± 57.7	0.520
HDL-C, mg/dL	63.0 ± 13.4	65.4 ± 15.2	63.9 ± 15.9	0.123	56.4 ± 14.6	56.9 ± 15.6	56.4 ± 15.1	0.913
LDL-C, mg/dL	120.5 ± 28.0	121.8 ± 27.9	121.4 ± 28.7	0.797	112.7 ± 27.5	111.6 ± 29.4	109.5 ± 26.5	0.399
HbA1c, %	5.8 ± 0.6	5.8 ± 0.6	5.8 ± 0.6	0.818	5.9 ± 0.8	5.9 ± 0.8	5.8 ± 0.6	0.215
Hemoglobin, g/dL	12.8 ± 1.1	12.8 ± 1.2	12.9 ± 1.3	0.624	14.0 ± 1.4	13.9 ± 1.6	14.0 ± 1.4	0.921

Data are presented as the mean ± SD or n (%).

* A higher PRAL value indicates a more acidogenic diet.

† P-values were obtained using the χ^2 test for categorical variables and the general linear model for continuous ones.BMI, body mass index; EER, estimated energy requirement; HbA1c, glycated hemoglobin; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; PRAL, potential renal acid load; SD, standard deviation; T, tertile.

Table 2
Nutritional intake at baseline in female participants.

	PRAL groups*				
	T1	T2	T3	P-values†	
	(*n* = 296)	(*n* = 297)	(*n* = 297)	Diff.	Trend
Energy and nutrients					
Energy, kcal/day	1,673.8 ± 529.4	1,894.4 ± 577.2	1,934.0 ± 622.1	<0.001	<0.001
Energy per BW, kcal/day	33.9 ± 12.3	40.0 ± 13.5	38.9 ± 14.3	<0.001	<0.001
Protein, g/day	72.7 ± 16.2	71.2 ± 17.1	81.4 ± 20.5	<0.001	<0.001
Protein per BW, g/day	1.4 ± 0.3	1.5 ± 0.3	1.6 ± 0.3	<0.001	<0.001
Animal protein, g/day	41.0 ± 14.5	42.7 ± 15.0	54.0 ± 19.0	<0.001	<0.001
Plant protein, g/day	31.7 ± 6.2	28.6 ± 5.6	27.4 ± 6.0	<0.001	<0.001
Animal protein ratio, %	54.9 ± 10.5	58.4 ± 9.4	64.9 ± 9.1	<0.001	<0.001
Protein energy ratio, %	16.8 ± 3.0	17.2 ± 3.1	18.7 ± 3.6	<0.001	<0.001
Carbohydrates energy ratio, %	55.0 ± 6.9	52.4 ± 7.3	49.1 ± 7.6	<0.001	<0.001
Fat energy ratio, %	28.1 ± 5.1	29.6 ± 5.3	30.4 ± 5.2	<0.001	<0.001
Alcohol, g/day	0.4 ± 1.7	0.7 ± 4.7	1.7 ± 6.3	0.002	0.001
Phosphorus, mg/day	1,163.9 ± 268.3	1,101.3 ± 284.2	1,235.9 ± 331.3	<0.001	0.003
Potassium, mg/day	3,559.3 ± 817.6	2,823.9 ± 722.3	2,698.8 ± 783.6	<0.001	<0.001
Calcium, mg/day	722.7 ± 212.5	626.6 ± 205.3	656.8 ± 224.8	<0.001	<0.001
Magnesium, mg/day	305.2 ± 66.9	262.3 ± 65.2	267.5 ± 72.8	<0.001	<0.001
Food groups					
Grains, g/1,000 kcal	159.7 ± 58.3	170.4 ± 65.8	179.5 ± 66.5	0.001	<0.001
Tubers and roots, g/1,000 kcal	47.3 ± 33.2	33.0 ± 20.3	25.1 ± 17.7	<0.001	<0.001
Sugar and Sweeteners, g/1,000 kcal	3.3 ± 2.5	3.2 ± 2.2	2.9 ± 1.8	0.059	0.025
Legumes, g/1,000 kcal	44.2 ± 29.0	41.5 ± 22.9	37.7 ± 27.4	0.012	0.003
Vegetables, g/1,000 kcal	245.3 ± 79.4	183.0 ± 56.4	142.6 ± 55.8	<0.001	<0.001
Fruits, g/1,000 kcal	157.5 ± 83.0	107.6 ± 52.6	84.2 ± 47.4	<0.001	<0.001
Fish and seafood, g/1,000 kcal	42.4 ± 25.1	52.7 ± 26.5	68.8 ± 35.1	<0.001	<0.001
Meats, g/1,000 kcal	38.3 ± 19.5	41.0 ± 20.5	46.7 ± 22.7	<0.001	<0.001
Eggs, g/1,000 kcal	27.2 ± 16.4	24.9 ± 13.2	28.3 ± 17.1	0.024	0.395
Milk and dairy, g/1,000 kcal	104.8 ± 71.0	93.2 ± 57.2	88.4 ± 60.6	0.005	0.002
Fat and oils, g/1,000 kcal	5.1 ± 2.5	5.7 ± 2.5	5.9 ± 2.5	0.001	<0.001
Confectionery, g/1,000 kcal	33.1 ± 23.2	39.0 ± 24.8	32.1 ± 23.4	0.001	0.631
Beverages, g/1,000 kcal	411.5 ± 204.9	322.0 ± 148.8	292.5 ± 164.2	<0.001	<0.001
Condiment, g/1,000 kcal	116.3 ± 68.7	122.4 ± 75.5	124.0 ± 74.1	0.401	0.200

Data are presented as the mean ± SD.

* A higher PRAL value indicates a more acidogenic diet.

† P-values for group difference and trend were obtained using the general linear model for continuous ones.BW, body weight; Diff., Difference; PRAL, potential renal acid load; SD, standard deviation; T, tertile.

Table 3
Nutritional intake at baseline in male participants.

	PRAL groups*				
	T1	T2	T3	P-values†	
	(*n* = 271)	(*n* = 272)	(*n* = 271)	Diff.	Trend
Energy and nutrients					
Energy, kcal/day	2,078.4 ± 583.6	2,159.4 ± 597.5	2,112.5 ± 646.9	0.299	0.515
Energy per BW, kcal/day	34.2 ± 10.7	36.9 ± 12.1	34.6 ± 11.5	0.013	0.678
Protein, g/day	85.8 ± 20.5	84.2 ± 19.9	95.3 ± 22.2	<0.001	<0.001
Protein per BW, g/day	1.4 ± 0.3	1.4 ± 0.3	1.5 ± 0.3	<0.001	<0.001
Animal protein, g/day	46.7 ± 18.4	49.5 ± 17.6	61.8 ± 21.4	<0.001	<0.001
Plant protein, g/day	39.1 ± 8.7	34.7 ± 7.1	33.5 ± 7.2	<0.001	<0.001
Animal protein ratio, %	52.9 ± 11.4	57.4 ± 9.7	63.4 ± 9.9	<0.001	<0.001
Protein energy ratio, %	15.6 ± 3.0	15.9 ± 3.1	17.4 ± 3.5	<0.001	<0.001
Carbohydrates energy ratio, %	52.8 ± 7.6	51.4 ± 8.1	48.8 ± 8.4	<0.001	<0.001
Fat energy ratio, %	27.1 ± 5.0	27.2 ± 5.3	28.5 ± 5.8	0.003	0.002
Alcohol, g/day	12.1 ± 18.3	13.8 ± 21.3	11.8 ± 18.0	0.410	0.861
Phosphorus, mg/day	1,367.3 ± 339.8	1,292.4 ± 336.7	1,426.6 ± 368.8	<0.001	0.048
Potassium, mg/day	4,045.3 ± 999.8	3,139.5 ± 822.9	2,965.4 ± 826.0	<0.001	<0.001
Calcium, mg/day	838.7 ± 265.2	713.8 ± 258.5	729.4 ± 264.6	<0.001	<0.001
Magnesium, mg/day	361.7 ± 86.0	305.7 ± 79.8	309.0 ± 79.0	<0.001	<0.001
Food groups					
Grains, g/1,000 kcal	168.7 ± 62.0	187.8 ± 65.3	196.0 ± 70.3	<0.001	<0.001
Tubers and roots, g/1,000 kcal	39.5 ± 30.4	26.4 ± 19.0	18.9 ± 16.7	<0.001	<0.001
Sugar and Sweeteners, g/1,000 kcal	3.0 ± 2.5	3.2 ± 2.5	3.2 ± 2.6	0.577	0.391
Legumes, g/1,000 kcal	43.5 ± 30.2	36.8 ± 27.9	34.5 ± 23.8	<0.001	<0.001
Vegetables, g/1,000 kcal	223.8 ± 81.1	151.5 ± 59.1	121.4 ± 51.0	<0.001	<0.001
Fruits, g/1,000 kcal	119.6 ± 66.0	81.6 ± 50.7	63.3 ± 39.9	<0.001	<0.001
Fish and seafood, g/1,000 kcal	38.7 ± 22.1	47.0 ± 26.8	63.3 ± 33.6	<0.001	<0.001
Meats, g/1,000 kcal	34.6 ± 19.2	37.4 ± 17.4	42.6 ± 20.7	<0.001	<0.001
Eggs, g/1,000 kcal	24.2 ± 14.8	24.1 ± 14.2	28.4 ± 16.6	0.001	0.001
Milk and dairy, g/1,000 kcal	91.4 ± 58.3	85.0 ± 63.5	74.3 ± 60.7	0.004	0.001
Fat and oils, g/1,000 kcal	5.5 ± 2.7	5.3 ± 2.3	6.0 ± 2.7	0.012	0.025
Confectionery, g/1,000 kcal	31.4 ± 23.6	33.5 ± 24.4	28.4 ± 21.5	0.034	0.124
Beverages, g/1,000 kcal	384.1 ± 192.8	351.1 ± 179.2	304.9 ± 165.8	<0.001	<0.001
Condiment, g/1,000 kcal	122.4 ± 65.6	127.9 ± 63.0	140.1 ± 74.8	0.008	0.002

Data are presented as the mean ± SD.

* A higher PRAL value indicates a more acidogenic diet.

† P-values for group difference and trend were obtained using the general linear model for continuous ones.BW, body weight; Diff., Difference; PRAL, potential renal acid load; SD, standard deviation; T, tertile.

Table 4
Multivariable-adjusted association between the incidence of disability and PRAL group.

PRAL groups*	Case/total, n (%)	Crude			Model 1			Model 2		
		OR	95 % CI	P-values†	OR	95 % CI	P-values†	OR	95 % CI	P-values†
Females										
T1	20/296 (6.8)	Ref.			Ref.			Ref.		
T2	20/297 (6.7)	1.00	0.52–1.89	0.991	1.08	0.562.08	0.827	1.10	0.57–2.13	0.781
T3	31/297 (10.4)	1.61	0.89–2.89	0.113	1.90	1.04–3.48	0.037	1.96	1.06–3.61	0.032
Males										
T1	16/271 (5.9)	Ref.			Ref.			Ref.		
T2	14/272 (5.1)	0.86	0.41–1.81	0.700	0.77	0.35–1.70	0.512	0.79	0.35–1.76	0.562
T3	14/271 (5.2)	0.87	0.42–1.82	0.707	0.79	0.36–1.73	0.558	0.81	0.37–1.79	0.601

* A higher PRAL value indicates a more acidogenic diet.

† P-values were obtained using multiple logistic regression analysis. Model 1: adjusted for age, BMI, and energy intake. Model 2: adjusted for Model 1 variables + living alone, current smoker, number of comorbidities of hypertension, diabetes, and dyslipidemia (i.e., 0 to 3).BMI, body mass index; CI, confidence interval; OR, odds ratio; PRAL, potential renal acid load; Ref, reference; SD, standard deviation; T, tertile.

spectively, in females and 0.79 (0.35–1.76) and 0.81 (0.37–1.79), respectively, in males.

4. Discussion

In this study, we followed community-dwelling older adults aged ≥ 75 years to investigate the association between dietary acid load and disability incidence. In females, diets with a high acid load, as assessed using PRAL (i.e., diets that were more likely to cause metabolic acidosis), were associated with disability. To the best of our knowledge, this is the first study to report a longitudinal association between diet that caused acidosis and functional disability for daily living.

Age-related reductions in urinary H^+ excretion combined with acidic diets are thought to predispose older adults to muscle wasting caused by mild metabolic acidosis [15]. Acidosis increases skeletal muscle catabolism. The amino acids released during this catabolism are converted to glutamine in the liver, which increases ammonia synthesis in the kidneys. Ammonia buffers H^+ and is then excreted as ammonium ions to alleviate acidosis [37]. Older patients with sarcopenia have lower urine pH values than those without sarcopenia [38]. The negative effects of dietary acid load on skeletal muscle function have been suggested; diets with a high acid load are associated with decreased skeletal muscle mass and symptoms of physical frailty, particularly slowness and weakness [16,39,40]. The decline in physical functions makes it difficult to maintain activities of daily living. According to a survey by the Japanese Cabinet Office, 26.3 % of the underlying reasons for needing long-term care can be attributed to factors associated with physical function decline, such as frailty and falls [41]. Based on the findings of previous studies, although our follow-up period was short, the intake of a diet capable of causing metabolic acidosis may have led to the incident disability.

In this study, sex-based differences were observed regarding the association between PRAL and disability. A high dietary acid load was found to be associated with the occurrence of disability only in female participants. Previous studies have also reported sex-based differences in the effects of PRAL. Faure et al. also reported a no[association between PRAL and lean body mass only in females [17]. A study examining the effect of bicarbonate intervention to relieve acidosis on lower extremity muscle strength reported that treatment was effective in females but not in males [42]. In a meta-analysis exploring the effect of dietary acid load on the development of type 2 diabetes, sub-analysis results showed that the effect was significant only in females [43]. Thus, although some studies have reported that dietary acid-base balance may exert a negative impact on health only in females, none have addressed the mechanism underlying sex-based differences in dietary acid load. Therefore, future research is warranted on this topic.

Although protein intake is crucial for maintaining physical function in older adults, protein is considered an acidogenic nutrient in PRAL calculations [8]. However, the protein intake in the T1 group meets the requirement for older individuals to maintain physical function [44]. Although meat and fish have higher acid loads [8], the T1 group consumed the equivalent of one fish and one meat dish per day, which is unlikely to be a low intake. Animal proteins have higher bioavailabilities than plant proteins such as beans [45]. Therefore, it may be important to avoid eating excess animal protein. While, the intake of vegetables and fruits rich in alkaline nutrients in the T3 group was approximately half of that in the T1 group. In contrast to protein-rich foods, vegetables and fruits produce alkalis [22]. These findings indicate that the T3 group may require an increased fruit and vegetable intake to reduce the elevated acid load due to animal protein intake. Although the optimal ratio of animal to plant protein is debated worldwide, the 55 % animal protein intake in the T1 group may provide important insights. Further research to clarify these findings would be worthwhile. Therefore, consuming a combination of protein-rich foods, as well as vegetables and fruits rich in alkaline nutrients such as potassium, may represent an important dietary strategy for maintaining physical function in older adults. Diets are influenced by different ethnicities and cultures; therefore, even if a diet is considered good for some countries, it may be difficult to adopt a similar diet in countries with different cultures. However, by determining the optimal proportions of food groups from PRAL values, they can be translated into different dietary patterns. This will have positive implications for public health measures across cultures.

This study had some limitations. First, the BDHQ was used to assess dietary intake, and nutrient intake was estimated based only on foods and dishes mentioned in the questionnaire; thus, the intake of some foods could not be estimated. However, the BDHQ was developed based on the general dietary habits of the Japanese population, and its validity has been demonstrated in previous studies [25,28]. Second, the BDHQ requires participants to review their meals over the previous month and report their frequency of intake; therefore, it may have been difficult for older individuals with cognitive impairments to provide accurate responses. However, our participants were excluded if their reports on the postal questionnaire (which included dietary assessments) were unreliable. Additionally, this study targeted participants who led self-reliant lives and could return the questionnaire by mail. Therefore, it is unlikely that the study included many individuals with substantial cognitive impairments. Third, we were unable to assess whether there were any foods that participants could not eat owing to food allergies or disease. Hypertension, diabetes, and dyslipidemia, which were used as covariates in this study, are the three major diseases most likely to receive dietary advice under the Japanese medical system, but adjustment for these factors alone may not be insufficient. Fourth, because this study was conducted during the coronavirus disease 2019 pandemic in 2021, the participants' lifestyles and dietary behaviors may have been influenced by their social conditions [46]. Fifth, we could not consider the history of stroke and ischemic heart diseases, which are associated with a high mortality risk, especially if the PRAL score is high [34]. Sixth, all included participants were able to complete a postal survey and had undergone health checkups. Therefore, the cohort may have been biased toward healthier and more health-conscious individuals. Finally, this study was conducted in a single region; therefore, the obtained results should be confirmed in other populations.

5. Conclusions

In community-dwelling Japanese females aged ≥ 75 years, a high-acid load diet was found to increase the incidence of disability. Although future research should investigate sex-based differences regarding the effects of PRAL, for older individuals who need high protein intake to prevent disability, diets rich in vegetables and fruits, along with protein-rich foods, may represent important dietary strategies.

Declaration of Competing Interest

The authors declare no conflicts of interest related to this study.

Acknowledgments

We are grateful to all of the participants and Higashiura municipal staff for their help and efforts related to this study. We also thank Editage (www.editage.com) for their assistance with English language editing.

Authors' contributions

Kaori Kinoshita, Conceptualization, Formal analysis, Methodology, Investigation, Funding acquisition, Writing-original draft, Writing-review, and Editing; Yosuke Osuka, Conceptualization, Methodology, Writing-review, and Editing; Kazuhiro Yoshiura, Conceptualization, Methodology, Writing-review, and Editing; Noriko Hori, Conceptualization, Methodology, Writing-review, and Editing; von Fingerhut Georg, Conceptualization, Methodology, Writing-review, and Editing; Shosuke Satake, Conceptualization, Methodology, Investigation, Funding acquisition, Project administration, Writing-review, and Editing; and Hidenori Arai, Conceptualization, Methodology, Project administration, Writing-review, and Editing. All authors critically revised the manuscript for intellectual content and approved its final version.

Sources of support

This study was supported in part by Research Funding for Longevity Sciences from the National Center for Geriatrics and Gerontology, Japan (grant no. 21-19) and JSPS KAKENHI (grant no. 22K17384). No grant provider played any role in the design, analysis, or writing of this manuscript.

Ethical Standards

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Human Research of the National Center for Geriatrics and Gerontology, Japan (No. 1532-2).

References

[1] The Lancet Healthy LongevityCare for ageing populations globally. Lancet Healthy Longev 2021;2:e180. doi:10.1016/S2666-7568(21)00064-7.

[2] Cruz-Jentoft AJ, Dawson Hughes B, Scott D, Sanders KM, Rizzoli R. Nutritional strategies for maintaining muscle mass and strength from middle age to later life: a narrative review. Maturitas 2020;132:57–64. doi:10.1016/j.maturitas.2019.11.007.

[3] Dent E, Morley JE, AJ Cruz-Jentoft, et al. International Clinical Practice Guidelines for Sarcopenia (ICFSR): Screening, Diagnosis and Management. J Nutr Health Aging 2018;22:1148–61. doi:10.1007/s12603-018-1139-9.

[4] Dent E, Morley JE, AJ Cruz-Jentoft, et al. Physical frailty: ICFSR International Clinical Practice Guidelines for Identification and Management. J Nutr Health Aging 2019;23:771–87. doi:10.1007/s12603-019-1273-z.

[5] Kelly OJ, Gilman JC, Ilich JZ. Utilizing dietary micronutrient ratios in nutritional research may be more informative than focusing on single nutrients. Nutrients 2018;10:107. doi:10.3390/nu10010107.

[6] Newby PK, Tucker KL. Empirically derived eating patterns using factor or cluster analysis: a review. Nutr Rev 2004;62:177–203. doi:10.1111/j.1753-4887.2004.tb00040.x.

[7] Solans M, Coenders G, Marcos-Gragera R, et al. Compositional analysis of dietary patterns. Stat Methods Med Res 2019;28:2834–47. doi:10.1177/0962280218790110.

[8] Remer T, Manz F. Potential renal acid load of foods and its influence on urine pH. J Am Diet Assoc 1995;95:791–7. doi:10.1016/S0002-8223(95)00219-7.

[9] Welch AA, MacGregor AJ, Skinner J, Spector TD, Moayyeri A, Cassidy A. A higher alkaline dietary load is associated with greater indexes of skeletal muscle mass in women. Osteoporos Int 2013;24:1899–908. doi:10.1007/s00198-012-2203-7.

[10] Remer T, Manz F. Estimation of the renal net acid excretion by adults consuming diets containing variable amounts of protein. Am J Clin Nutr 1994;59:1356–61. doi:10.1093/ajcn/59.6.1356.

[11] Price SR, Du JD, Bailey JL, Mitch WE. Molecular mechanisms regulating protein turnover in muscle. Am J Kidney Dis 2001;37:S112–14. doi:10.1053/ajkd.2001.20764.

[12] Williams B, Layward E, Walls J. Skeletal muscle degradation and nitrogen wasting in rats with chronic metabolic acidosis. Clin Sci (Lond) 1991;80:457–62. doi:10.1042/cs0800457.

[13] May RC, Kelly RA, Mitch WE. Metabolic acidosis stimulates protein degradation in rat muscle by a glucocorticoid-dependent mechanism. J Clin Invest 1986;77:614–21. doi:10.1172/JCI112344.

[14] Owen EE, Robinson RR. Amino acid extraction and ammonia metabolism by the human kidney during the prolonged administration of ammonium chloride. J Clin Invest 1963;42:263–76. doi:10.1172/JCI104713.

[15] Frassetto L, Morris RC Jr, Sellmeyer DE, Todd K, Sebastian A. Diet, evolution and aging–the pathophysiologic effects of the post-agricultural inversion of the potassium-to-sodium and base-to-chloride ratios in the human diet. Eur J Nutr 2001;40:200–13. doi:10.1007/s394-001-8347-4.

[16] Chan R, Leung J, Woo J. Association between estimated net endogenous acid production and subsequent decline in muscle mass over four years in ambulatory older Chinese people in Hong Kong: a prospective cohort study. J Gerontol A Biol Sci Med Sci 2015;70:905–11. doi:10.1093/gerona/glu215.

[17] Faure AM, Fischer K, Dawson-Hughes B, Egli A, Bischoff-Ferrari HA. Gender-specific association between dietary acid load and total lean body mass and its dependency on protein intake in seniors. Osteoporos Int 2017;28:3451–62. doi:10.1007/s00198-017-4220-z.

[18] Dawson-Hughes B, Harris SS, Ceglia L. Alkaline diets favor lean tissue mass in older adults. Am J Clin Nutr 2008;87:662–5. doi:10.1093/ajcn/87.3.662.

[19] Ceglia L, Harris SS, Abrams SA, Rasmussen HM, Dallal GE, Dawson-Hughes B. Potassium bicarbonate attenuates the urinary nitrogen excretion that accompanies an increase in dietary protein and may promote calcium absorption. J Clin Endocrinol Metab 2009;94:645–53. doi:10.1210/jc.2008-1796.

[20] Dawson-Hughes B, Harris SS, Palermo NJ, Castaneda-Sceppa C, Rasmussen HM, Dallal GE. Treatment with potassium bicarbonate lowers calcium excretion and bone resorption in older men and women. J Clin Endocrinol Metab 2009;94:96–102. doi:10.1210/jc.2008-1662.

[21] Frassetto L, Morris RC Jr, Sebastian A. Potassium bicarbonate reduces urinary nitrogen excretion in postmenopausal women. J Clin Endocrinol Metab 1997;82:254–9. doi:10.1210/jcem.82.1.3663.

[22] Storz MA, Ronco AL, Hannibal L. Observational and clinical evidence that plant-based nutrition reduces dietary acid load. J Nutr Sci 2022;11:e93. doi:10.1017/jns.2022.93.

[23] Higashiura Town. Official statistics. https://www.town.aichi-higashiura.lg.jp/. Accessed 29 July 2024.

[24] Ministry of Health Labour and Welfare Japan. Long-term care insurance system 2019. https://www.mhlw.go.jp/content/12300000/000614772.pdf. Accessed 29 July 2024.

[25] Kobayashi S, Honda S, Murakami K, et al. Both comprehensive and brief self-administered diet history questionnaires satisfactorily rank nutrient intakes in Japanese adults. J Epidemiol 2012;22:151–9. doi:10.2188/jea.JE20110075.

[26] Kobayashi S, Yuan X, Sasaki S, et al. Relative validity of brief-type self-administered diet history questionnaire among very old Japanese aged 80 years or older. Public Health Nutr 2019;22:212–22. doi:10.1017/S1368980018002331.

[27] Ministry of Health Labour and Welfare. National Health and Nutrition Survey. http://www.nibiohn.go.jp/eiken/english/research/project_nhns.html. Accessed 26 September 2024.

[28] Kobayashi S, Murakami K, Sasaki S, et al. Comparison of relative validity of food group intakes estimated by comprehensive and brief-type self-administered diet history questionnaires against 16 d dietary records in Japanese adults. Public Health Nutr 2011;14:1200–11. doi:10.1017/S1368980011000504.

[29] Sasaki S, Yanagibori R, Amano K. Self-administered diet history questionnaire developed for health education: a relative validation of the test-version by comparison with 3-day diet record in women. J Epidemiol 1998;8:203–15. doi:10.2188/jea.8.203.

[30] Ministry of Education, Culture, Sports, Science, and Technology-Japan. Standard Tables of Food Composition Japan-2015- (Seventh Revised Version). https://www.mext.go.jp/en/policy/science_technology/policy/title01/detail01/1374030.htm. Accessed 26 September 2024.

[31] Murakami K, Livingstone MBE, Fujiwara A, Sasaki S. Reproducibility and relative validity of the healthy eating index-2015 and nutrient-rich food index 9.3 estimated by Comprehensive and Brief Diet History Questionnaires in Japanese adults. Nutrients 2019;11:2540. doi:10.3390/nu11102540.

[32] Ministry of Health, Labour and Welfare-Japan. Dietary reference intakes for Japanese (2020). https://www.mhlw.go.jp/content/10904750/000586553.pdf. Accessed 26 September 2024.

[33] Frassetto LA, Todd KM, Morris RC Jr, Sebastian A. Estimation of net endogenous noncarbonic acid production in humans from diet potassium and protein contents. Am J Clin Nutr 1998;68:576–83. doi:10.1093/ajcn/68.3.576.

[34] Akter S, Nanri A, Mizoue T, et al. Dietary acid load and mortality among Japanese men and women: the Japan public health center-based prospective study. Am J Clin Nutr 2017;106:146–54. doi:10.3945/ajcn.117.152876.

[35] Mohammadpour S, Djafari F, Davarzani S, Djafarian K, Clark CCT. Shab-Bidar S. The association between dietary acid load and muscle strength among Iranian adults. BMC Res Notes 2020;13:476. doi:10.1186/s13104-020-05309-6.

[36] Murakami K, Sasaki S, Takahashi Y, et al. Dietary glycemic index and load in relation to metabolic risk factors in Japanese female farmers with traditional dietary habits. Am J Clin Nutr 2006;83:1161–9. doi:10.1093/ajcn/83.5.1161.

[37] Mithal A, Bonjour JP, Boonen S, et al. Impact of nutrition on muscle mass, strength, and performance in older adults. Osteoporos Int 2013;24:1555–66. doi:10.1007/s00198-012-2236-y.

[38] Saitsu A, Iwazu Y, Matsushita H, Hayashi H, Mizuhashi Y, Kotani K. Low urine pH associated with sarcopenia in the elderly: a multi-center observational study. Medicine (Baltimore) 2021;100:e26114. doi:10.1097/MD.0000000000026114.

[39] Hayhoe RPG, Abdelhamid A, Luben RN, Khaw KT, Welch AA. Dietary acid-base load and its association with risk of osteoporotic fractures and low estimated skeletal muscle mass. Eur J Clin Nutr 2020;74:33–42. doi:10.1038/s41430-020-0686-4.

[40] Kataya Y, Murakami K, Kobayashi S, Suga H, Sasaki S. Higher dietary acid load is associated with a higher prevalence of frailty, particularly slowness/weakness, and low physical activity, in elderly Japanese women. Eur J Nutr 2018;57:1639–50. doi:10.1007/s00394-017-1449-4.

[41] Cabinet Office, Government of Japan. White paper on older people. 2022. https://www8.cao.go.jp/kourei/whitepaper/w-2022/html/zenbun/s1_2_2.html. Accessed 26 September 2024.

[42] Dawson-Hughes B, Castaneda-Sceppa C, Harris SS, et al. Impact of supplementation with bicarbonate on lower-extremity muscle performance in older men and women. Osteoporos Int 2010;21:1171–9. doi:10.1007/s00198-009-1049-0.

[43] Jayedi A, Shab-Bidar S. Dietary acid load and risk of type 2 diabetes: a systematic review and dose-response meta-analysis of prospective observational studies. Clin Nutr ESPEN 2018;23:10–18. doi:10.1016/j.clnesp.2017.12.005.

[44] Bauer J, Biolo G, Cederholm T, et al. Evidence-based recommendations for optimal dietary protein intake in older people: a position paper from the PROT-AGE Study Group. J Am Med Dir Assoc 2013;14:542–59. doi:10.1016/j.jamda.2013.05.021.

[45] Food Agriculture Organization of the United NationsDietary protein quality evaluation in human nutrition: Report of an FAO Expert Consultation. FAO Food and Nutrition Paper 2013;92. https://books.google.co.jp/books?id=_V9UmwEACAAJ Accessed 26 September 2024.

[46] Kinoshita K, Satake S, Arai H. Impact of frailty on dietary habits among community-dwelling older persons during the COVID-19 pandemic in Japan. J Frailty Aging 2022;11:109–14. doi:10.14283/jfa.2021.45.