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Original Communication

Associations Between Calcium Intake, Functional Ability, and Healthcare Costs: A Prospective Cohort Study

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Abstract

Background: Calcium is an essential dietary element and the most abundant mineral in the human body; moreover, calcium is critical for health. Nonetheless, a significant proportion of Chinese adults fail to meet dietary calcium recommendations. Therefore, this study aimed to assess the associations between sufficient calcium intake, functional ability, and healthcare costs among older adults in China. **Methods:** Nationwide panel data from the China Health and Nutrition Survey (CHNS) were analyzed for 3127 adults aged ≥55 years from 219 communities across nine provinces. Dietary intake was measured using three consecutive 24-hour recalls, and calcium intake was calculated using the Chinese Food Composition Tables. Calcium sufficiency was defined as an intake of ≥800 mg/day, based on the 2023 Dietary Reference Intake for China. Functional ability was assessed using the Lawton–Brody Instrumental Activities of Daily Living (IADL) index. Fixed-effects linear regression models were used to evaluate associations with functional ability and healthcare costs. **Results:** Only 30.5% of participants met the recommended calcium intake, with a mean intake of 689 mg/day. Calcium sufficiency was associated with a 0.09-point higher overall IADL score ($p < 0.01$), with stronger associations among adults aged ≥65 years (0.29; $p < 0.001$), women (0.17; $p < 0.001$), non-married individuals (0.38; $p < 0.001$), those with an elementary school education or less (0.14; $p = 0.02$), and individuals with chronic conditions (0.28; $p < 0.001$). Calcium sufficiency was also associated with a 7.8% reduction in four-week healthcare expenditures (Chinese Yuan [CNY] 8.77 or US Dollar [USD] 1.25), corresponding to approximately CNY 114 (USD 16.3) in annual savings. Stronger associations with healthcare expenditures were observed among socioeconomically and health-vulnerable subgroups. **Conclusions:** Calcium intake insufficiency is widespread among older adults in China and is associated with lower functional ability and higher healthcare costs. Meanwhile, improving calcium intake is associated with meaningful gains in functional independence and lower healthcare expenditures, particularly among vulnerable populations.

Keywords: calcium; dietary; functional ability; functional independence; healthcare costs

1. Introduction

Calcium intake is essential for maintaining overall health and supporting essential bodily functions [1]. As the primary mineral in bones and teeth, calcium is critical for maintaining strength and density [2], playing a pivotal role in preventing osteoporosis and fractures [3,4], particularly among older adults [4]. Beyond its contributions to skeletal health, calcium also supports vital physiological processes, including muscle contraction, nerve transmission, blood clotting, and cardiovascular function [5]. Furthermore, adequate calcium intake has been linked to the regulation of blood pressure and may reduce the risk of chronic diseases, such as hypertension and certain cancers, underscoring its broader health significance [6].

Independence in Instrumental Activities of Daily Living (IADLs) is a crucial indicator of an individual's ability to live self-sufficiently and maintain quality of life [7,8]. IADLs include tasks such as managing finances, handling medications, preparing meals, and completing household chores, all of which require a combination of physical and cognitive functioning [9,10]. Declines in IADL performance often signal early functional impairments, enabling healthcare providers to identify individuals at risk of dependency, falls, or hospitalizations [11]. Understanding the factors associated with IADL performance is essential for developing interventions that promote aging-in-place, thereby reducing the financial burden associated with long-term care and improving the quality of life for older adults.

Research on calcium intake and IADLs remains limited. To our knowledge, only one study has examined the association between calcium intake and impaired activities of daily living (ADL) [12]. ADL reflects basic self-care tasks such as feeding, dressing, bathing, toileting, and indoor walking. Unlike ADLs, IADLs capture earlier and more subtle functional limitations, exhibit greater variation in community-dwelling populations, and are more closely associated with healthcare utilization, caregiving needs, and loss of independent living. This makes IADLs particularly relevant for analyses of functional ability and healthcare costs. The earlier study, conducted in Japan, found an

inverse association between calcium intake and ADL impairment ten years after baseline [12]. A related study in South Korea reported that frequent consumption of milk and dairy products was inversely associated with IADL disability among older men [13]. However, the role of calcium cannot be isolated given the presence of multiple nutrients in dairy products. To date, no study has directly examined the association between calcium intake and IADLs, nor has the literature explored how calcium intake relates to healthcare costs through functional ability.

Analysis of the association between calcium intake and IADLs is particularly urgent in China due to the rapidly aging population and high prevalence of osteoporosis [14,15]. With more than 20% of the population expected to be over 60 years old by 2035 [16], age-related functional impairments such as IADL limitations pose a significant public health concern [17]. Furthermore, dietary calcium intake in China remains below global standards [18]. Investigating this relationship can guide public health initiatives (e.g., dietary education, supplementation programs) to improve bone health, independence, and support healthy aging in China [19,20].

The economic implications of calcium intake further highlight its importance. Conditions such as osteoporosis and fractures, which calcium intake helps prevent, are significant contributors to healthcare costs, particularly in aging societies [21,22]. Ensuring sufficient calcium intake may reduce the incidence of these conditions, thereby improving IADL performance and mitigating healthcare expenditures related to medical treatments, hospitalizations, and long-term care [23,24,25]. Exploring the relationship between calcium intake, functional ability, and healthcare costs can inform public health policies and strategies to enhance nutritional interventions and reduce the economic burden on healthcare systems. The aim of this study was therefore to evaluate the associations between calcium intake sufficiency, functional ability, and healthcare costs, thus providing critical insights for improving public health outcomes.

2. Method

2.1 Study Population

This analysis utilized data from the China Health and Nutrition Survey (CHNS) (accessible via https://chns.cpc.unc.edu/), a nationwide prospective cohort study conducted between 1989 and 2022. The CHNS collected comprehensive information on nutrition, health behaviors, socioeconomic factors, and health outcomes. Participants were recruited using a multistage randomized sampling method from 15 provinces and municipal cities in China. All participants provided written informed consent, and the study was approved by institutional review boards at both the University of North Carolina at Chapel Hill (UNC-CH) and the Chinese Center for Disease Control and Prevention (CDC).

Our analysis draws on data from the 2004 and 2006 waves, the only survey years in which information on IADLs was collected. The initial sample comprised 5815 adult-year observations. We excluded 1361 observations with missing key control variables (see Table 1 for details) and an additional 25 observations due to age reporting errors, as IADL questions were administered only to adults aged 55 years and older. The final analytic sample includes 3127 adults from 219 communities across nine provinces in China, yielding a total of 4429 adult-year observations.

2.2 Measurement of Calcium Intake Sufficiency

The CHNS collected individual dietary data over three consecutive, randomly assigned days using 24-hour recalls. These were cross-validated with household food inventory data. Household food inventories were constructed by trained nutritionists weighing all food items, including purchases, home-produced foods, and waste. The records were reconciled with individual recalls to ensure internal consistency, and any discrepancies were verified through follow-up visits. All field staff were trained nutritionists with prior experience in national dietary surveys. Nutrient intakes were calculated using updated Chinese Food Composition Tables developed collaboratively by UNC-CH and the Chinese National Institute of Nutrition and Food Safety [26,27]. The study used the recommended nutrient intake (RNI) for calcium from the 2023 Dietary Reference Intake for China as the lower bound (daily calcium intake ≥800 mg). If a respondent's intake of calcium intake equaled or exceeded the lower bound, their calcium intake was considered to be sufficient for the individual (calcium intake sufficiency = 1, 0 otherwise).

Calcium intake was measured using a binary indicator of sufficiency rather than modeling intake as a continuous variable or in quantiles. This approach aligns the exposure with established nutritional guidelines and emphasizes adequacy versus inadequacy, which is more interpretable and policy-relevant than marginal differences [28]. Modeling calcium intake continuously or in quantiles implicitly assumes a linear or monotonic association with functional outcomes. Such an assumption that is unlikely given evidence of threshold effects in micronutrient adequacy [28]. Moreover, dietary recall data are subject to substantial measurement error and day-to-day variation, which can attenuate associations when intake is modeled continuously. On the other hand, dichotomizing at an established cutoff reduces noise from minor reporting differences around similar intake levels [29]. Using a sufficiency-based measure therefore improves interpretability, comparability across studies, and robustness in analyses linking calcium intake to functional ability and healthcare costs.

2.3 Assessment of Functional Ability and Healthcare Costs

This study evaluated the functional ability of older adults using the Lawton-Brody Index of IADL, a widely

Table 1. Characteristics of adults with sufficient and insufficient calcium intake.

Variables		Deficient calcium intake (n = 3077)	Sufficient calcium intake (n = 1352)	*p-value*
Calcium intake (mg/day)		468 ± 181	1,191 ± 462	<0.001
Lawton-Brody index of independence in instrumental activities of daily living (IADL), mean ± SD		4.6 ± 1.0	4.8 ± 0.7	<0.001
Age, mean ± SD		65.5 ± 8.1	64.6 ± 7.3	<0.001
Number of chronic diseases, mean ± SD		0 [0, 0]	0 [0, 1]	<0.001
Male, n (%)		1375 (45%)	641 (47%)	0.09
Han ethnicity, n (%)		2582 (84%)	1242 (92%)	<0.001
Rural Hukou, n (%)		1857 (60%)	572 (42%)	<0.001
Residence, n (%)				<0.001
	City	295 (10%)	207 (15%)	
	Suburban	651 (21%)	434 (32%)	
	Town or county capital	487 (16%)	208 (15%)	
	Rural village	1644 (53%)	503 (37%)	
Married, n (%)		2372 (77%)	1115 (82%)	<0.001
Education, n (%)				<0.001
	Elementary school	2420 (79%)	880 (65%)	
	Middle school	443 (14%)	278 (21%)	
	High school and above	214 (7%)	194 (14%)	
Medical insurance, n (%)				<0.001
	NRCMS	510 (17%)	254 (19%)	
	Other insurance	541 (18%)	482 (36%)	
	No insurance	2026 (66%)	616 (46%)	
Alcohol drinking, n (%)				0.02
	None	2254 (73%)	936 (69%)	
	Light	167 (5%)	91 (7%)	
	Moderate	162 (5%)	78 (6%)	
	Heavy	494 (16%)	247 (18%)	
Smoking, n (%)				0.50
	Current	820 (27%)	368 (27%)	
	Former	191 (6%)	95 (7%)	
	Never	2066 (67%)	889 (66%)	
BMI status, n (%)				<0.001
	Underweight	292 (9%)	79 (6%)	
	Normal	1704 (55%)	662 (49%)	
	Overweight	824 (27%)	456 (34%)	
	Obese	257 (8%)	155 (11%)	
Daily energy intake (kcal/day)		2191 ± 771	2942 ± 758	<0.001

***Notes**:* NRCMS, New Rural Cooperative Medical Scheme; BMI, Body Mass Index; SD, standard deviation. Continuous variables are presented as means ± standard deviation (SD) while categorical variables are presented as numbers (%). The number of chronic diseases is presented as median [IQR]. The *p* values were calculated using the chi-squared test for categorical variables or the *t*-test for continuous variables. Mann–Whitney U test was performed to compare the number of chronic diseases between groups.

used tool for assessing independence in performing instrumental daily tasks [20,30]. The IADL index includes eight activities: cooking, grocery shopping, making phone calls, managing finances, using transportation, housekeeping, medication management, and laundry. However, due to limitations in the CHNS dataset, information on housekeeping, medication management, and laundry was not collected. As a result, this study focused on the first five activities to assess participants' self-care abilities and functional independence . The IADL index was scored based on levels of difficulty: no difficulty (1 point), difficulty but able to complete the task independently (1 point), requiring assistance (0 points), and inability to complete the task (0 points). The total score ranged from 0 to 5, with higher scores indicating greater independence in performing instrumental daily activities.

We assign the same score to "no difficulty" and "difficulty but able to complete independently" because the IADL index is intended to measure functional independence rather than perceived task difficulty. Consistent with

the original IADL framework, the key distinction is whether an individual can perform an activity without assistance, as dependence or inability represents a meaningful threshold for disability, loss of independent living, and healthcare needs [20]. Collapsing the difficulty levels also reduces subjectivity in self-reported difficulty and improves comparability across individuals and survey waves, a common practice in population-based studies of functional status [31].

Healthcare costs were measured as the sum of inpatient and outpatient expenses incurred by participants during the four weeks preceding the data collection period.

2.4 Confounders

This study incorporated covariates commonly associated with functional ability and healthcare costs, as identified in the literature [19,32,33]. These variables, available in the CHNS database, included demographic, socioeconomic, behavioral, and health-related factors. Specifically, the control variables included demographic characteristics (age, sex, ethnicity, marital status, and place of residence), socioeconomic indicators (Hukou status and highest level of education attained), behavioral variables (alcohol consumption frequency and smoking status), health conditions (Body Mass Index [BMI] and number of chronic diseases), types of medical insurance and daily energy intake.

Health insurance status was classified into three categories: New Rural Cooperative Medical Scheme (NRCMS), other types of insurance, and no insurance. NRCMS is a government-subsidized health insurance program for rural residents in China and generally provides less coverage and lower reimbursement rates than urban insurance schemes. Other types of insurance primarily include employer-sponsored and government-sponsored urban insurance programs, which are concentrated among urban residents and offer more comprehensive benefits. We control for insurance type to account for differences in healthcare access and reimbursement levels across insurance systems.

Alcohol consumption was categorized as none, light drinking (once or twice per month), moderate drinking (once or twice per week), and heavy drinking (three or more times per week). BMI was classified into four categories: underweight (<18.5), normal weight (18.5–24), overweight (24–28), and obese (≥28). China's BMI categories have lower thresholds for overweight and obesity compared to WHO standards (≥25 for overweight and ≥30 for obesity) due to the higher body fat percentage of Asians and increased risk of chronic diseases at lower BMI levels [34]. These adjusted cutoffs reflect population-specific health data, genetic predispositions, and cultural factors, allowing for more accurate identification of individuals at risk in China [34].

The Hukou system, introduced in China during the 1950s, is a household registration system that classifies individuals as rural or urban residents based on their birthplace. This system has a profound impact on access to education, healthcare, and housing [35,36]. Urban Hukou holders typically enjoy better public services and job opportunities, while rural Hukou holders face significant barriers, even when living in cities, perpetuating socioeconomic inequalities [37]. Although recent reforms have aimed to reduce these disparities, the Hukou system continues to shape China's social and economic landscape [38].

Ethnicity was included as a covariate to account for its potential influence on calcium intake and related outcomes. Cultural dietary practices and healthcare access disparities tied to ethnicity can significantly affect calcium intake levels and functional or health outcomes. CHNS categorized participants as Han (the majority ethnicity) or various minority groups, including Mongolian, Hui, Tibetan, Uygur, Miao, Yi and others.

2.5 Statistics

For summary statistics, continuous variables are reported as means ± standard deviation (SD), and categorical variables as counts and percentages. p values were calculated using chi-squared tests for categorical variables, Mann–Whitney U test for count of chronic disease, t-tests for continuous variables, comparing calcium-sufficient and calcium-deficient observations.

Associations between calcium intake sufficiency and functional ability were examined using fixed-effects linear regression models that included province and year fixed effects. Province fixed effects accounted for time-invariant regional characteristics, including baseline health conditions, healthcare infrastructure, dietary patterns, and socioeconomic environments, while year fixed effects captured common temporal shocks and national trends. Although the IADL index is ordinal, linear models were used because functional limitation indices are commonly analyzed as quasi-continuous measures, and linear estimates approximate average marginal associations from ordered response models when outcomes have multiple categories [39,40]. The analytical focus was on average differences in functional ability associated with calcium intake sufficiency rather than category-specific probabilities. Linear fixed-effects models also avoid the additional assumptions and potential incidental-parameters bias associated with nonlinear fixed-effects estimators in short panels [41].

Associations between functional ability and healthcare expenditures were examined using fixed-effects linear regression models with province and year fixed effects. Healthcare costs were modeled using ordinary least squares despite the presence of zero expenditures, as the objective was to estimate differences in total expected expenditures rather than utilization conditional on any use [41]. In this context, zero expenditures were interpreted as reflecting low utilization during the observation window rather than a distinct participation decision. Linear fixed-effects mod-

els provided a parsimonious and interpretable framework while avoiding additional assumptions and small-sample concerns associated with nonlinear two-part models with fixed effects [41].

Lastly, the association between calcium intake sufficiency and healthcare costs operating through functional ability (IADL) was summarized using a product-of-coefficients approach. Specifically, the estimated coefficient on calcium intake sufficiency from the IADL regression was multiplied by the estimated coefficient on IADL from the healthcare costs regression. This approach characterized the indirect association between calcium intake sufficiency and healthcare expenditures through functional status and is commonly used in the mediation and health economics literature when linear models are estimated separately [42,43,44]. Decomposition in this manner provided a transparent summary of the extent to which differences in functional ability were associated with differences in healthcare costs across calcium intake sufficiency groups.

All regression models were adjusted for the confounders outlined in the previous section. Stratified (effect-modification) analyses were conducted by including interaction terms between calcium sufficiency and modifiers in the IADL regressions, where modifiers were specified using the same set of covariates as in the main models. In addition, interaction terms between IADL and the same modifiers were included in the healthcare costs regressions to allow the association between functional status and healthcare expenditures to vary across subgroups. This unified interaction-based approach enables consistent assessment of heterogeneity along both the calcium–IADL and IADL–cost pathways.

Statistical significance was assessed using two-sided *t*-tests, with a *p*-value of <0.05 considered statistically significant. All analyses were conducted using Stata MP 16.0 (StataCorp LLC, College Station, TX, USA). This study utilizes publicly available secondary data, which does not require ethical approval or informed consent.

3. Results

3.1 Basic Characteristics of Subjects by Calcium Intake Sufficiency

Table 1 compares baseline characteristics according to calcium intake sufficiency, highlighting the persistently low level of calcium intake among older adults in China. Only 30.5% of participants met the recommended threshold for calcium sufficiency. Moreover, the average dietary calcium intake of 689 mg/day was well below the recommended level of 800 mg/day.

Individuals with sufficient calcium intake consumed substantially more calcium (1191 vs. 468 mg/day) and had higher total energy intake (2942 vs. 2191 kcal/day) than those with insufficient intake. Calcium-sufficient participants also exhibited higher functional ability, as reflected by a higher mean IADL index (4.8 vs. 4.6), and were slightly younger on average (64.6 vs. 65.5 years). All differences were statistically significant ($p < 0.001$).

Socio-demographic characteristics differed significantly between the two groups. Calcium-sufficient individuals were more likely to be of Han ethnicity (92% vs. 84%), married (82% vs. 77%), hold an urban Hukou (58% vs. 40%), and reside in urban (15% vs. 10%) or suburban areas (32% vs. 21%) compared to calcium-insufficient individuals (all $p < 0.001$). Educational attainment was higher in the calcium-sufficient group, with a greater share completing high school or higher education (14% vs. 7%; $p < 0.001$). Calcium-sufficient group was also more likely to be covered by other types of insurance (36% vs. 18%; $p < 0.001$).

Lifestyle and health characteristics varied according to calcium intake status, with calcium-sufficient participants more likely to be heavy drinkers (18% vs. 16%), overweight (34% vs. 27%), or obese (11% vs. 8%) compared to their calcium-deficient counterparts (all $p < 0.02$).

3.2 Association Between Calcium Intake Sufficiency and Functional Ability

Fig. 1 displays the coefficient estimates and 95% confidence intervals (CIs) from fixed-effects linear regression models examining the association between calcium intake sufficiency and the IADL score across selected individual characteristics. Overall, calcium intake sufficiency was associated with a 0.09-point higher IADL score ($p = 0.003$). This association was stronger among adults aged 65 years and older (0.29 vs. –0.07; $p < 0.001$), women (0.17 vs. 0.01; $p < 0.001$), and non-married individuals (0.38 vs. 0.02; $p < 0.001$). The positive association between calcium sufficiency and functional ability was also more pronounced among participants with elementary school as their highest level of education (0.14 vs. –0.01; $p = 0.02$), never consumed alcohol (0.14 vs. –0.01; $p = 0.02$), never smoked (0.14 vs. 0.003; $p = 0.02$), reported chronic disease (0.28 vs. 0.03; $p < 0.001$), and had daily energy intake below the sample median of 2350 kcal (0.18 vs. 0.05; $p = 0.02$) when compared to their respective counterparts.

3.3 Association Between Functional Ability and Healthcare Costs

Fig. 2 summarizes the association between IADL score and healthcare expenditures. Overall, a one-point increase in the IADL score was associated with a reduction of 97.49 yuan in healthcare spending over the preceding four weeks ($p < 0.001$). For reference, one U.S. dollar is approximately equivalent to seven Chinese yuan.

The magnitude of the cost-reducing association varied across subgroups. A one-point increase in IADL was associated with larger reductions in healthcare costs among younger adults than older adults (–126.3 vs. –98.06 yuan; $p = 0.004$). Similarly, stronger associations were observed among individuals of urban Hukou holders (–137.47 vs. –61.68 yuan; $p = 0.01$), residents of cities, suburbs, or town-

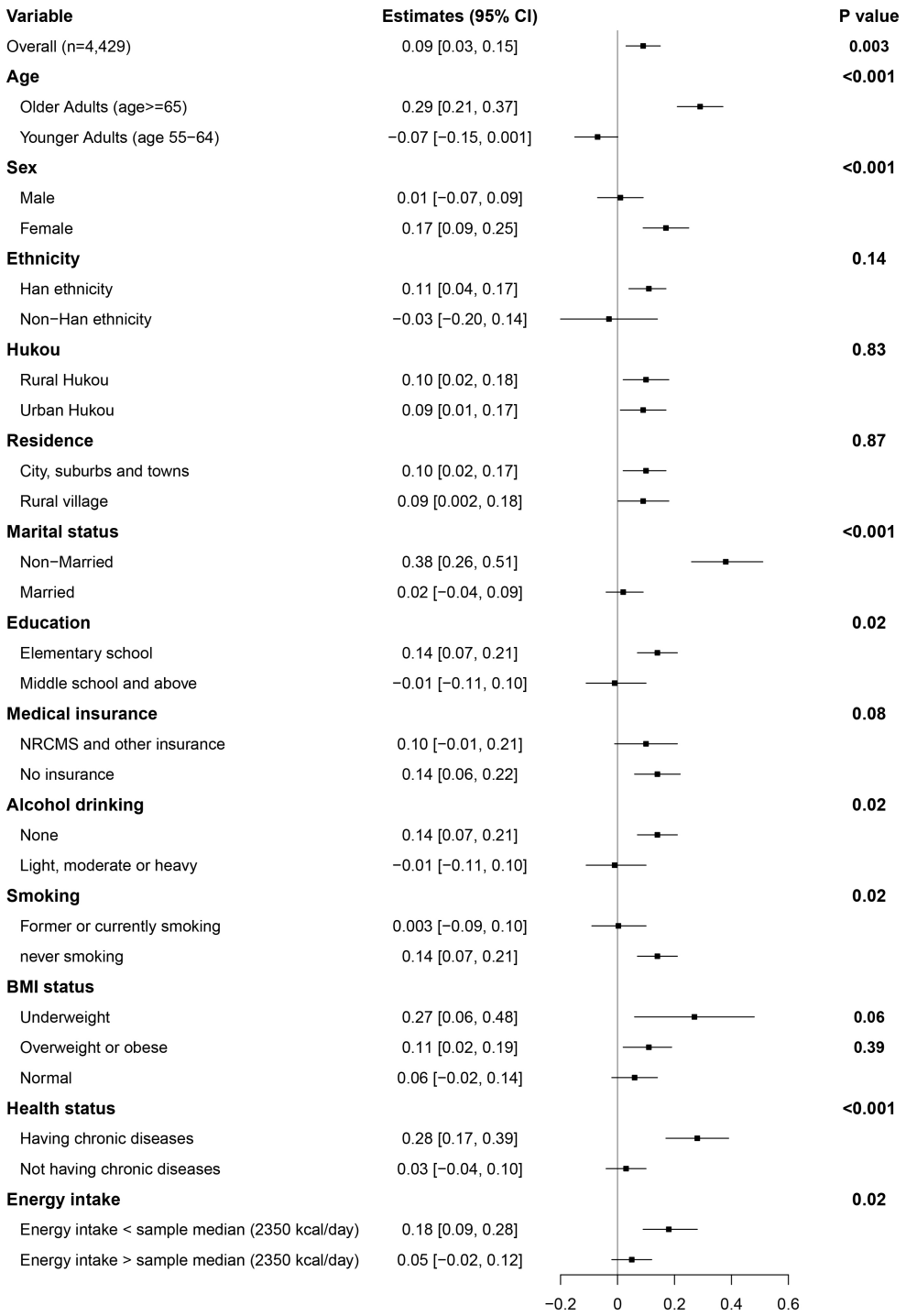

Fig. 1. Stratified estimates for the associations between sufficient calcium intake and independence in Instrumental Activities of Daily Living (IADL). ***Notes*** : NRCMS, New Rural Cooperative Medical Scheme; BMI, Body Mass Index. The figure reports coefficient estimates and 95% confidence intervals (CIs) from fixed-effects linear regression models of the IADL index on calcium intake sufficiency interacted with individual characteristics. *p*-values correspond to the interaction terms and indicate whether the association between calcium sufficiency and IADL differs across subgroups. All regressions adjust for age, sex, Han ethnicity, rural Hukou status, residence type, marital status, education, medical insurance type, drinking status, smoking status, BMI category, presence of chronic diseases, and daily energy intake.

ships (–136.01 vs. –45.30 yuan; $p = 0.003$), married individuals (–146.37 vs. –36.64 yuan; $p < 0.001$), insured individuals (–152.73 vs. –74.53 yuan; $p = 0.02$), and those who never consumed alcohol (–116.40 vs. –13.08 yuan; $p = 0.01$), compared to their respective counterparts.

By contrast, we found no evidence that the association between IADL score and healthcare costs differed by sex, educational attainment, smoking status, BMI category, health status as measured by the presence of chronic diseases, or daily energy intake.

3.4 Association Between Calcium Intake Sufficiency and Healthcare Costs

Table 2 summarizes the differences in healthcare costs changes associated with calcium sufficiency operating through functional ability (IADL). These estimates were derived using a product-of-coefficients approach, multiplying the coefficient on calcium sufficiency from the IADL regression (Fig. 1; Column 2 of Table 2) by the coefficient on IADL from the healthcare costs regression (Fig. 2; Column 1 of Table 2). To facilitate interpretation, the resulting estimates were scaled by the sample-average healthcare costs, and differences were reported as a percentage.

Overall, calcium sufficiency was associated with a reduction of 8.77 yuan in healthcare spending over the preceding four weeks through improvement in IADL, relative to an average four-week healthcare costs of 112.22 yuan in the sample. This corresponds to a 7.8% reduction in healthcare expenditures during the 2004–2006 survey period. As a back-of-the-envelope calculation, this four-week reduction is annualized by multiplying the estimated savings by 13 (13 four-week periods per year), yielding approximately 114.01 yuan in annual healthcare costs savings if similar effects persist throughout the year.

The reduction in healthcare costs associated with calcium sufficiency was more pronounced among older adults (–20.94% vs. 9.72%), women (–14.42% vs. –0.88%), non-married individuals (–20.46% vs. –2.36%), individuals of Han ethnicity (–9.50% vs. 1.22%), and those with only an elementary school education (–12.16% vs. 0.45%). Larger cost reductions were also observed among participants who never consumed alcohol (–13.15% vs. 0.16%), never smoked (–12.14% vs. –0.24%), reported chronic diseases (–9.77% vs. –4.42%), and had daily energy intake below the sample median (–19.33% vs. –3.55%) when compared to their respective counterparts.

4. Discussion

Our findings highlight persistently low calcium intake among older adults in China. In our sample, only 30.5% of adults met the Chinese Recommended Nutrient Intake (RNI) for calcium (800 mg/day), with an average intake of 689 mg/day. By comparison, recommended intakes are higher in Western countries. For example, the Recommended Dietary Allowance (RDA) in the United States is 1000 mg/day for men aged 51–70 years and 1200 mg/day for women aged ≥51 years and all individuals aged ≥71 years, while European recommendations generally range from 950 to 1200 mg/day [45]. Consistent with these guidelines, average calcium intake in North America and most European countries typically exceeds 900–1000 mg/day, whereas intake in many Asian countries, including China, remains substantially lower [46]. These cross-country differences largely reflect longstanding variation in dietary patterns, particularly lower dairy consumption in China [46]. In the context of rapid population aging, such widespread calcium insufficiency may have important implications for functional independence, healthcare utilization, and long-term economic burden.

Consistent with this concern, calcium intake sufficiency was positively associated with functional ability, as measured by independence in IADLs. Calcium sufficiency emerged as an independent protective factor and was associated with a 0.09-point higher IADL score, indicating greater functional ability among calcium-sufficient adults relative to their calcium-deficient counterparts. These results align with previous research affirming the significant role of calcium in supporting physical function and reducing disability risks [12]. Moreover, calcium sufficiency was linked to lower healthcare costs, with annual healthcare expenses being 114.01 yuan (7.8%) lower for calcium-sufficient individuals. These economic benefits demonstrate the potential for substantial cost savings at both the individual and societal levels, presenting a valuable opportunity for improving health outcomes and reducing healthcare expenditures in China.

The biological mechanisms underlying the association between calcium intake sufficiency and functional ability remain to be fully elucidated. Calcium plays a central role in bone mineralization, slows bone loss [47], and strengthens skeletal structures, which collectively reduce fracture risk and enhance mobility [48]. Additionally, calcium supports neuromuscular function by facilitating muscle contraction and nerve signaling, thereby improving coordination, balance, and overall physical performance [48,49]. These physiological effects likely contribute to the maintenance of independence in daily activities, the prevention of falls, and the enhancement of functional well-being in calcium-sufficient individuals.

The stronger associations observed between calcium intake sufficiency and functional ability observed among older adults, women, individuals with elementary school education, and those with chronic diseases carry significant implications. Our findings suggest that targeted efforts to improve calcium intake could particularly benefit these vulnerable groups, who are at higher risk of functional decline due to health disparities and limited access to resources. For example, older adults and individuals with chronic diseases may experience improved mobility and reduced disability risks with adequate calcium intake. Similarly, addressing calcium insufficiency among less-educated populations could help reduce health inequalities and improve quality of life by supporting functional independence [50,51].

The association between calcium intake sufficiency and healthcare costs was more pronounced among older

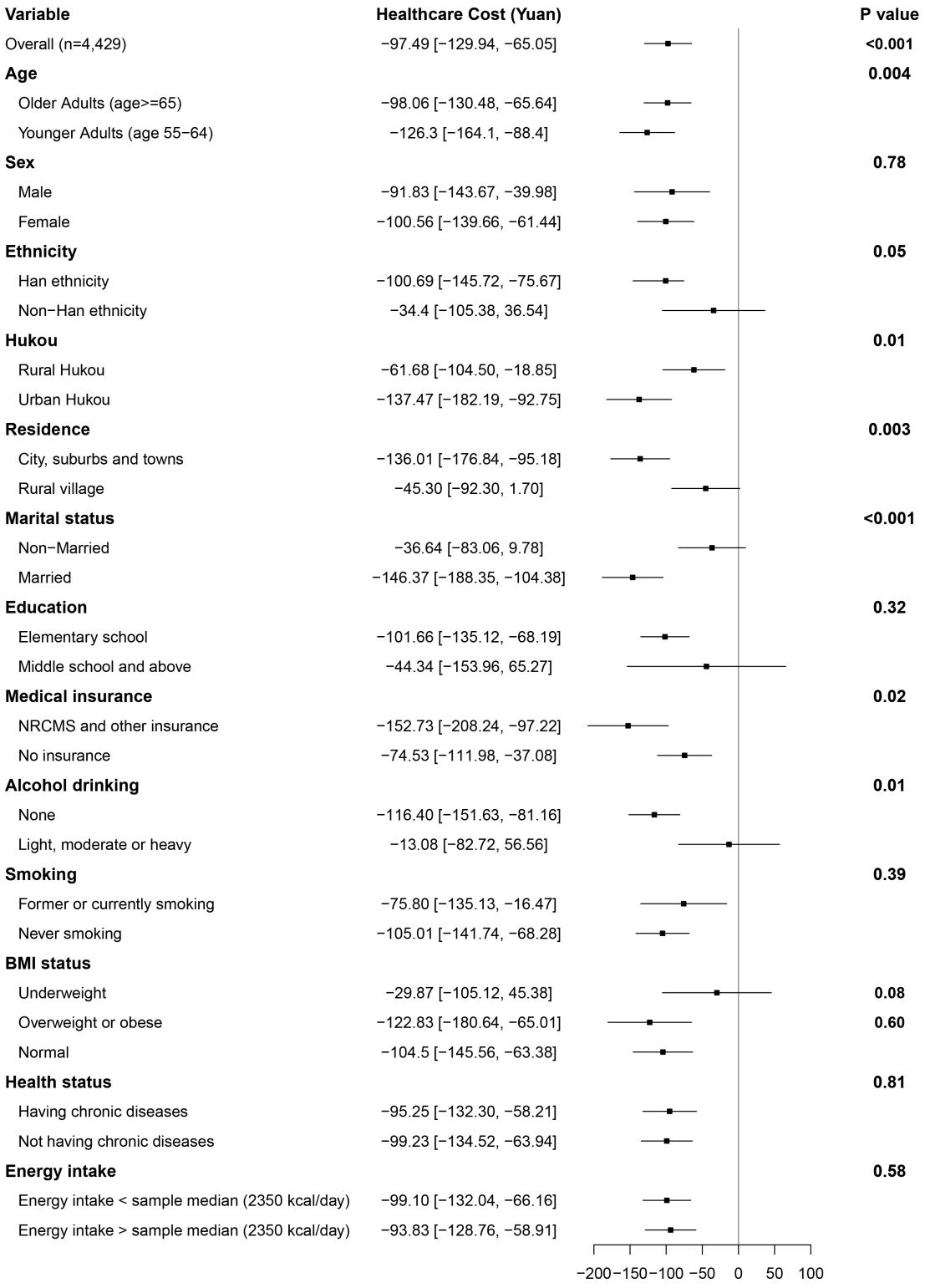

Fig. 2. Stratified estimates for the associations between IADL score and healthcare costs. ***Notes*** : NRCMS, New Rural Cooperative Medical Scheme; BMI, Body Mass Index. The figure reports coefficient estimates and 95% confidence intervals from fixed-effects linear regression models of the healthcare costs on IADL scores, interacted with individual characteristics. *p*-values correspond to the interaction terms and indicate whether the association between IADL and healthcare costs differs across subgroups. All regressions are adjusted for age, sex, Han ethnicity, rural Hukou status, residence type, marital status, education, medical insurance type, drinking status, smoking status, BMI category, presence of chronic disease, and daily energy intake.

Table 2. Stratified estimates for the associations between sufficient calcium intake and healthcare costs (n = 4429).

Variables	Healthcare Costs	IADL	Healthcare Costs Change Associated with Calcium Sufficiency (Yuan)	Sample Average Healthcare Costs (Yuan)	Healthcare Costs Change Associated with Calcium Sufficiency (%)
Overall	–97.49	0.09	–8.77	112.22	–7.82%
Age	$p = 0.004$	$p < 0.001$			
Older Adults (age ≥65)	–98.06	0.29	–28.44	135.82	–20.94%
Younger Adults (age 55–64)	–126.27	–0.07	8.84	90.99	9.72%
Sex	$p = 0.78$	$p < 0.001$			
Male	–91.83	0.01	–0.92	104.61	–0.88%
Female	–100.56	0.17	–17.10	118.57	–14.42%
Ethnicity	$p = 0.05$	$p = 0.14$			
Han ethnicity	–100.69	0.11	–11.08	116.58	–9.50%
Non–Han ethnicity	–34.42	–0.03	1.03	84.62	1.22%
Hukou	$p = 0.01$	$p = 0.83$			
Rural Hukou	–61.68	0.10	–6.17	71.46	–8.64%
Urban Hukou	–137.47	0.09	–12.37	161.71	–7.65%
Residence	$p = 0.003$	$p = 0.87$			
City, suburbs and towns	–136.01	0.10	–13.60	163.58	–8.31%
Rural village	–45.30	0.09	–4.08	57.63	–7.08%
Marital status	$p < 0.001$	$p < 0.001$			
Non–Married	–36.64	0.38	–13.92	68.06	–20.46%
Married	–146.37	0.02	–2.93	124.15	–2.36%
Education	$p = 0.32$	$p = 0.02$			
Elementary school	–101.66	0.14	–14.23	116.98	–12.16%
Middle school and above	–44.34	–0.01	0.44	98.29	0.45%
Medical insurance	$p = 0.02$	$p = 0.08$			
NRCMS and other insurance	–152.73	0.10	–15.27	137.44	–11.11%
No insurance	–74.53	0.14	–10.43	95.15	–10.96%
Alcohol drinking	$p = 0.01$	$p = 0.02$			
None	–116.4	0.14	–16.30	123.91	–13.15%
Light, moderate or heavy	–13.08	–0.01	0.13	82.12	0.16%
Smoking	$p = 0.39$	$p = 0.02$			
Former or currently smoking	–75.80	0.003	–0.23	94.40	–0.24%
Never smoking	–105.01	0.14	–14.70	121.11	–12.14%
BMI status	$p = 0.60/0.08$	$p = 0.39/0.06$			
Underweight	–29.87	0.27	–8.06	107.15	–7.52%
Overweight or obese	–122.83	0.11	–13.51	155.10	–8.71%
Normal	–104.47	0.06	–6.27	82.35	–7.61%
Health status	$p = 0.81$	$p < 0.001$			
Having chronic diseases	–95.25	0.28	–26.67	273.12	–9.77%
Not having chronic diseases	–99.23	0.03	–2.98	67.45	–4.42%

Table 2. Continued.

Variables	Healthcare Costs	IADL	Healthcare Costs Change Associated with Calcium Sufficiency (Yuan)	Sample Average Healthcare Costs (Yuan)	Healthcare Costs Change Associated with Calcium Sufficiency (%)
Energy intake	$p = 0.58$	$p = 0.02$			
Energy intake < sample median (2350 kcal/day)	–99.10	0.18	–17.84	92.34	–19.33%
Energy intake > sample median (2350 kcal/day)	–93.83	0.05	–4.69	132.12	–3.55%

***Notes**:* NRCMS, New Rural Cooperative Medical Scheme; BMI, Body Mass Index. This table reports the changes in healthcare costs associated with calcium sufficiency operating through functional ability (IADL) in Column 3. Estimates are obtained using a product-of-coefficients approach, calculated by multiplying the coefficient on calcium sufficiency from the IADL regression (Fig. 1; Table 2, Column 2) by the coefficient on IADL from the healthcare costs regression (Fig. 2; Table 2, Column 1). The resulting estimates are scaled by the sample-average healthcare costs (Column 4) and reported as percentage changes in Column 5. All regressions adjusted for age, sex, Han ethnicity, rural Hukou status, residence type, marital status, education, medical insurance type, drinking status, smoking status, BMI category, presence of chronic diseases, and daily energy intake. *p*-values were calculated using *t*-tests to assess differences in IADL and healthcare costs across subgroups. For BMI status, these *p*-values correspond to comparisons of underweight and overweight/obese groups with the normal-weight reference group.

adults, women, non-married individuals, individuals of Han ethnicity, and those with only an elementary school education. Larger cost reductions were also observed among participants who never consumed alcohol, never smoked, reported chronic diseases, and had daily energy intake below the sample median. These patterns are consistent with prior evidence showing that older adults, women, and socioeconomically disadvantaged groups face higher risks of musculoskeletal decline, disability, and healthcare utilization, making them more responsive to improvements in micronutrient adequacy [49,52]. Individuals with chronic conditions and lower overall energy intake may also have poorer baseline nutritional status, amplifying the marginal benefits associated with calcium sufficiency [53,54]. Together, these findings suggest that the economic benefits associated with calcium sufficiency may be concentrated among more vulnerable subpopulations, underscoring the potential value of targeted nutritional strategies for reducing functional decline and healthcare costs in aging populations.

This study also highlights the importance of addressing calcium intake insufficiency to support functional ability and manage healthcare costs. Practical interventions such as routine calcium deficiency screenings, targeted supplementation, and educational programs for patients and caregivers could help bridge the nutritional gap [55,56]. Policymakers might consider integrating these strategies into public health initiatives, including community health programs and primary care services, to improve accessibility and equity [57]. Additionally, subsidies for calcium supplements and culturally tailored educational campaigns could enhance the reach and impact of such interventions, particularly among vulnerable groups like the elderly population.

Despite its contributions, this study has several limitations. First, dietary intake is self-reported and therefore subject to measurement error and potential underreporting. Data constraints also preclude strong causal inference regarding the relationships between calcium intake sufficiency, functional ability, and healthcare costs. Calcium adequacy is closely linked to overall dietary patterns and correlated with the intake of other nutrients. Although we adjusted for daily energy intake to account for differences in total food consumption, we cannot fully isolate the independent association of calcium from broader dietary quality or correlated micronutrient adequacy. In addition, the analysis relies on two survey waves from 2004 and 2006, thus limiting our ability to capture longer-run dynamics.

An additional limitation is the lack of direct measures of vitamin D status, which may confound the observed associations. Vitamin D plays a central role in calcium absorption and is independently associated with musculoskeletal health, muscle strength, and the risk of falls [49,58,59]. To the extent that higher calcium intake is correlated with higher vitamin D status through diet, supplementation, or related health behaviors, our estimates may partly reflect the combined influence of both nutrients. However, vitamin D insufficiency is highly prevalent among Chinese adults, particularly among the older population [60,61,62]. While residual confounding cannot be ruled out, our results should be interpreted as associations within a nutritional environment characterized by widespread calcium and vitamin D insufficiency.

Despite these above limitations, this study is the first to use nationwide data from China to examine the associations between calcium intake sufficiency, functional ability, and healthcare costs, thereby providing an important foundation for future research. Further studies could clar-

ify causal mechanisms, evaluate interventions such as calcium supplementation and dietary education, and examine interactions between calcium and other nutrients such as vitamin D, which was not collected in the CHNS. Cross-country comparative analyses and the use of digital tools, such as mobile applications and wearable devices, may also improve the measurement and monitoring of calcium intake, thereby informing evidence-based policies aimed at promoting functional health and reducing healthcare expenditures.

5. Conclusion

This study documents a persistently low level of calcium intake among older adults in China, with only 30.5% meeting the recommended intake levels. The average intake of 689 mg/day, well below national recommendations and levels observed in developed countries. Calcium intake sufficiency was associated with a 0.09-point higher IADL score and a 7.8% (114.01 yuan) reduction in annual healthcare expenditures. These associations were stronger among older adults, women, and other socioeconomically vulnerable groups, highlighting the urgent need for targeted interventions. Strategies such as routine screening, calcium supplementation, educational programs, and culturally tailored initiatives could play an important role in improving functional health and reducing healthcare costs. Future research should focus on clarifying the causal relationships between calcium intake, functional ability, and healthcare costs, as well as cross-country analysis to enhance the generalizability of the current findings.

Availability of Data and Materials

The data and code will be available upon request.

Author Contributions

LF: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing; YP: Investigation, Writing – original draft, Writing – review & editing; XT: Investigation, Data curation , Writing – review & editing; AC: Conceptualization, Methodology, Writing – Review & Editing; YD: Conceptualization, Methodology, Writing – Review & Editing. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study only used publicly available survey data that are completely de-identified. There is no interaction or intervention with living individuals and the data cannot be linked back to individual identities. Hence it is not considered as research involving human participants under the U.S. federal definition per 45 CFR 46. In this case, IRB review is exempted.

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Conflicts of Interest

AC and YD are employed by Haleon. We had full access to all of the data in this study and we take complete responsibility for the integrity of the data and the accuracy of the data analysis. The other authors declare no conflicts of interest. MedSci. Inc had no role in the collection, analysis, and interpretation of the data; in the writing of the report; or in the decision to submit the paper for publication. The funder did not influence the results/outcomes of the study.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used OpenAI's ChatGPT 5.5 to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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