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Association between indoor ventilation frequency and low muscle mass among older adults in China: a national cross-sectional research

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Previous studies have established associations between indoor air pollution and *loss of* muscle mass. While indoor ventilation improves indoor air quality, its association with low muscle mass (LMM) remains unexplored. We investigated the association between indoor ventilation frequency (IVF) and LMM in older Chinese adults. Utilizing data from the China Longitudinal Healthy Longevity Survey (CLHLS), IVF was assessed via self-reported weekly window-opening frequency in each season of the past year. LMM was defined using appendicular skeletal muscle mass (ASM) prediction equations. Binary logistic regression models were employed to evaluate the association between IVF and LMM, with subgroup and sensitivity analyses conducted. After adjusting for covariates, participants with intermediate IVF (OR: 0.805; 95% CI: 0.669–0.969) and high IVF (OR: 0.818; 95% CI: 0.684–0.979) were 19.5% and 18.2% less likely to develop LMM, compared with participants with low IVF. The probability of LMM in the spring was 25.3% (OR: 0.747; 95% CI: 0.581–0.961) and 23.3% (OR: 0.767; 95% CI: 0.597–0.985) lower in the middle and high IVF elderly populations, respectively, whereas the probability of LMM in the spring was 36.5% (OR: 0.625; 95% CI: 0.474–0.824) and 34.1% (OR: 0.659; 95% CI: 0.501–0.868). The association between IVF and LMM was statistically significant ($p < 0.05$) in gender, age, residence, living arrangement, marital status, economic situation, work, smoking, drinking, exercise, cooking ventilation, life satisfaction, self-rated health, hypertension, diabetes, heart disease, dementia, and NO_2. Interaction analyses showed a significant interaction effect between the drinking subgroup and IVF (P for interaction < 0.05). Higher IVF is significantly associated with a lower risk of LMM. Optimizing ventilation practices may mitigate LMM burden in older adults, informing personalized health strategies.

Keywords Indoor ventilation frequency, Low muscle mass, Sarcopenia, Older adults, CLHLS

Sarcopenia is a progressive, age-related systemic disease characterized by a significant loss of skeletal muscle mass, strength, and function[1]. Globally, the prevalence of sarcopenia ranges from about 6–22%, making it a significant public health concern in aging populations[2]. As a core indicator of clinical assessment, the quantitative measurement of muscle mass plays an essential role in diagnosing and managing sarcopenia[3]. The muscle mass index is widely used to assess skeletal muscle health and has been validated in numerous studies[4,5]. Loss of muscle mass–a hallmark of the aging process, is strongly associated with disability, reduced mobility, falls, fractures, and increased mortality[6]. However, despite the increasing risks of sarcopenia, specific pharmacological treatments for low muscle mass (LMM) are still under investigation. Currently, muscle mass management still relies mainly on nutritional and exercise interventions, with neuromuscular electrical stimulation therapies are increasingly being applied in clinical practice[7–9] .

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Notably, in addition to traditional factors such as age, exercise, and nutrition[10,11], the influence of environmental exposures on muscle homeostasis is gaining increasing attention. Several studies have shown that the decline in muscle mass is related to air pollutants, including $PM_{2.5}$ (Particulate Matter 2.5), CO (Carbon Monoxide) and NO_2 (Nitrogen Dioxide)[12–14]. Notably, a study has shown that modern people spend around 90% of their time in indoor environments, making indoor air quality a key factor in health[15]. A significant body of research has examined the adverse health outcomes (e.g., cardiovascular disease, respiratory diseases, and mortality) caused by indoor air pollution[16,17], highlighting the importance of focusing on indoor air quality. Previous studies have also indicated that, in addition to the impact of outdoor air pollution on muscle mass loss, indoor air pollution may also contribute to muscle mass loss, especially for older Chinese adults who spend extended periods at home[18,19]. Using cooking fuels can seriously affect indoor air quality and increase the concentration of airborne pollutants such as $PM_{2.5}$[20,21]. A national study revealed that the incidence of sarcopenia was 4.5% lower among individuals using clean fuel for cooking, 2.9% lower among those using it for heating, and 3.0% and 1.9% higher among solid fuel users for cooking and heating, respectively[22].

Indoor ventilation, a key method for improving indoor air quality, effectively reduces pollutant concentrations by introducing fresh air into the indoor spaces, either naturally (e.g., through open windows) or mechanically (e.g., using air conditioning), thereby mitigating their adverse effects on health[23,24]. For example, a European study of nursing homes found that enhanced indoor ventilation was effective in mitigating the adverse effects of indoor air quality on the health of older residents and significantly improved overall quality of life[25]. Additionally, epidemiological studies have shown that higher indoor ventilation frequency (IVF) is associated with reduced risk of allergic symptoms, respiratory diseases and cognitive function in young people in developed regions[26–28]. Currently, there are no reports examining the impact of quantifiable IVF on muscle mass. Most environmental health studies focus primarily on cardiorespiratory or metabolic outcomes, with limited exploration of muscle mass. To date, no studies have quantified the effect of IVF on LMM.

To fill this research gap, this study, based on data from the 2017–2018 China Longitudinal Healthy Longevity Survey (CLHLS), aimed to explore the association between IVF and LMM, providing new ideas for the development of individualised health management strategies.

Materials and methods

Data source and sample

This study utilized data from the CLHLS, conducted by Peking University's Research Center for Aging Health and Development. CLHLS utilized a targeted random sample design to ensure the representativeness and reliability of the sample, providing comprehensive and extensive data on the healthcare status, caregiving, and medical requirements of older individuals in China. The detailed information regarding the CLHLS has been previously published[29,30].

The 2018 CLHLS conducted interviews with a total of 15,874 participants. Excluding those participants with missing information on IVF, LMM and covariates, 9,708 participants were finally included in the analysis (Fig. 1). The project has obtained approval from the Biomedical Ethics Committee of Peking University, China (IRB00001052-13074).

Indoor ventilation frequency

IVF was assessed based on the frequency of window opening per week in each season over the past year, as self-reported by the participants. Items were scored as follows: 0 points for 0 occurrences per week, 1 point for 1–5 occurrences per week, and 2 points for more than 5 occurrences per week. The IVF score, ranging from 0 to 8, was calculated by summing the individual IVF scores for each season. Scores of 0 to 3, 4 to 5, and 6 to 8 represent low, intermediate, and high IVF levels, respectively[31,32].

Low muscle mass

According to the criteria established by the Asian Working Group for Sarcopenia, muscle mass was primarily assessed using appendicular skeletal muscle mass (ASM), measured by bioelectrical impedance analysis and dual energy X-ray absorptiometry[33]. However, the instruments required for these methods are expensive, bulky, and necessitate rigorous training, which limits their application in community settings. Kawakami, R et al. used anthropometric and physical function parameters to develop equations for estimating muscle mass[34], providing a simple method for assessing muscle mass, and the method has been widely used in Chinese populations[35]. Therefore, our study evaluated LMM using an ASM prediction equation derived from weight, height, waist circumference, and calf circumference.The ASM prediction equation was: ASM (kg) = 2.955 * sex (male = 1, female = 0) + 0.255 * weight (kg) + 0.081 * height (cm) − 0.130 * waist circumference (cm) + 0.308 * calf circumference (cm)-11.897[34]. LMM was defined as < 7.0 kg*m^{-2} in males and < 5.7 kg*m^{-2} in females, calculated by multiplying ASM with height squared[35].

Covariates

To ensure the authenticity and reliability of the research results and minimize the potential influence of confounding variables, we implemented control measures for several covariates associated with IVF and muscle mass, based on a review of relevant literature. Specifically, these covariates included age (65–79, ≥ 80), gender (male, female), residence (rural, urban), living arrangement (living with family, other), education (0, 1–6, > 6 years), marital status (married, widowed, single, divorced), economic situation (good, average, poor), work (manual labor, other), smoking (yes, no), drinking (yes, no), exercise (yes, no), cooking fuel (renewable clean energy, other), cooking ventilation (yes, no), life satisfaction (good, average, poor), self-rated health (good, average, poor), hypertension (yes, no), diabetes (yes, no), heart disease (yes, no), dementia (yes, no), insurance

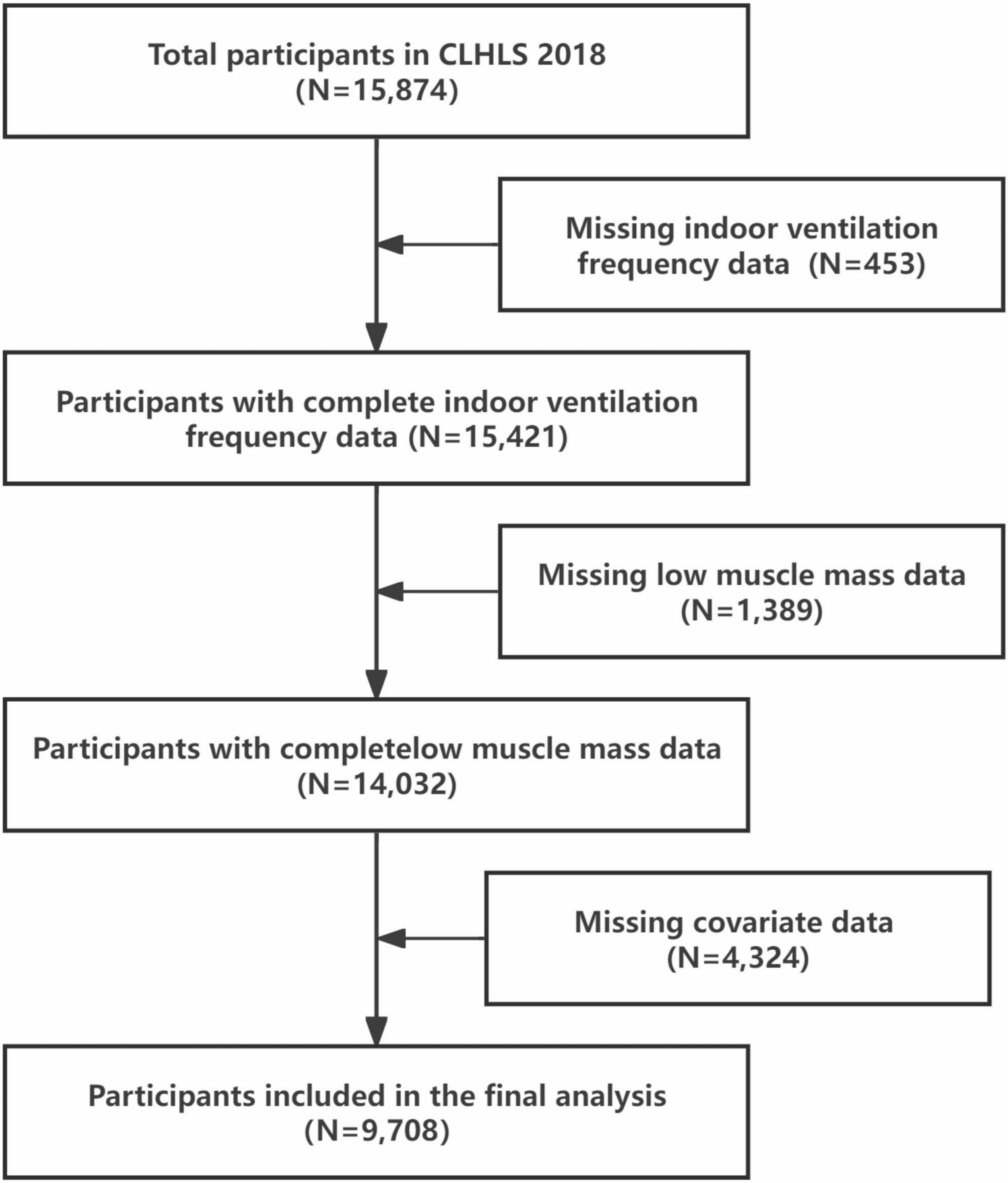

Fig. 1. Flowchart for the study design and participants.

(yes, no), $PM_{2.5}$ (quartiles), NO_2 (quartiles). Detailed assignment and classification criteria are provided in Supplementary Table 1.

Statistical analysis

The basic characteristics of the study sample across LMM and IVF were delineated by descriptive analysis. Categorical variables that fit a normal distribution are described as percentages (n(%)). Categorical variables were compared between subjects with different demographic characteristics using chi-square tests. Binary logistic regression model was used to evaluate the association between IVF and LMM. Three models were fitted to this study: Model 1 was a crude model that did not account for any covariates; Model 2 adjusted for gender, age, residence, living arrangement, education, marital status, economic situation, work, smoking, drinking, exercise, cooking fuel, cooking ventilation; Model 3 further adjusted for life satisfaction, self-rated health, hypertension, diabetes, heart disease, dementia, insurance, $PM_{2.5}$, NO_2. The study also conducted subgroup analyses of gender, age, residence, living arrangement, education, marital status, economic situation, work, smoking, drinking, exercise, cooking fuel, cooking ventilation, life satisfaction, self-rated health, hypertension, diabetes, heart disease, dementia, insurance, $PM_{2.5}$, NO_2 based on Model 3 and calculated interaction effects of subgroup variables. We performed two sensitivity analyses to assess the robustness of the results. First, we used chained equations to interpolate missing values to ensure a thorough examination of the dataset. Second, recognizing the unreliability of self-reported data from older people with dementia, we excluded participants with dementia from the analysis. The statistical analysis was conducted using the SPSS 27.0 software package. The criterion for statistical significance was set at a level of $P < 0.05$.

Results

Basic characteristics of the participant

Table 1 describes the presence or absence of LMM in different basic characteristics of the included participants. Of the 9,708 participants in this study, 6,048 (62.30%) suffered from LMM. 61.26% of participants were aged older than or equal to 80 years of age, 54.30% were male, and 43.16% lived in rural areas.The chi-square test showed that there was a significant difference ($p < 0.05$) between those with LMM and without LMM in the gender, age, residence, education, marital status, economic situation, work, drinking, exercise, cooking fuels, cooking ventilation, life satisfaction, self-rated health, hypertension, diabetes, and heart disease groups.

Table 2 shows different IVFs with different basic characteristics of the participants. More than half of the participants (59.03%) ventilated their homes six to eight times a week, 32.15% 4 to 5 times, and 8.82% only 1 to 3 times. Participants grouped with different IVF showed statistically significant differences ($p < 0.05$) between gender, age, residence, living arrangement, education, marital status, economic status, work, smoking, exercise, cooking fuel, cooking ventilation, life satisfaction, self-rated health, insurance, and NO_2.

Association between indoor ventilation frequency and low muscle mass

There are significant differences between seasonal and overall IVF and muscle mass ($P < 0.001$) (Table 3). Participants with LMM in older adults were observed to have a notably greater prevalence of low IVF and a lower prevalence of high IVF compared to those without LMM in each season.

In model 3, which was adjusted for various factors, participants with intermediate IVF (OR: 0.805; 95% CI: 0.669–0.969) and high IVF (OR: 0.818; 95% CI: 0.684–0.979) were 19.5% and 18.2% less likely to develop LMM, respectively, compared with participants with low IVF (Table 4).

The association between LMM and IVF by season was investigated in Model 3 (Table 5). Significant associations between IVF and LMM were observed only in spring and winter. Compared with the low IVF population, the probability of LMM in the spring was 25.3% (OR: 0.747; 95% CI: 0.581–0.961) and 23.3% (OR: 0.767; 95% CI: 0.597–0.985) lower in the middle and high IVF elderly populations, respectively, whereas the probability of LMM in the spring was 36.5% (OR: 0.625; 95% CI: 0.474–0.824) and 34.1% (OR: 0.659; 95% CI: 0.501–0.868), respectively.

Subgroup analysis

We considered 22 subgroups such as age-sex and further observed consistency in the association of IVF with LMM. The association between IVF and LMM was statistically significant ($p < 0.05$) for gender, age, residence, living arrangement, marital status, economic situation, work, smoking, drinking, exercise, cooking ventilation, life satisfaction, self-rated health, hypertension, diabetes, heart disease, dementia, and NO_2 (Fig. 2). Further interaction analyses showed a significant interaction effect between the drinking subgroup and IVF (P for interaction < 0.05).

Sensitivity analyses

Two sensitivity analyses conducted in the fully adjusted model 3 demonstrate the robustness of our findings. The first used chained-equation multiple interpolation to deal with missing data (Supplementary Table 2), and the second excluded participants with dementia, both of which showed that a statistically significant association between IVF and LMM existed ($P < 0.001$) (Supplementary Table 3).

Discussion

LMM is prevalent in older adults and is associated with many adverse outcomes, such as falls, metabolic disease, and mortality, demonstrating the value of LMM research[36,37] In the present day, individuals have allocated over 90% of their time within enclosed spaces, underscoring the significance of upholding optimal indoor air quality and mitigating potential airborne pollutants according to indoor ventilation as pivotal elements in preserving overall well-being[15]. This nationally representative study found that higher IVF was associated with a lower risk of LMM and observed that the association between IVF and LMM varied across subgroups.

Our study provides a new finding that high IVF may be a protective factor for LMM. Numerous studies have confirmed the correlation between indoor ventilation and improved home air quality[38,39] .For example, DuJ et al. showed that indoor ventilation was effective in improving indoor air quality and reducing pollutants in the absence of outdoor pollution and under favourable climatic conditions[32]. Through a literature review, we identified several studies reporting the association and intrinsic mechanisms between indoor air quality and

Variables	Total (*n* = 9708)	Without LMM (*n* = 3660)	With LMM (*n* = 6048)	Statistic	*P*
Gender, n (%)				χ^2=267.72	**< 0.001**
Female	5271 (54.30)	1598 (30.32)	3673 (69.68)		
Male	4437 (45.70)	2062 (46.47)	2375 (53.53)		
Age, n (%)				χ^2=942.27	**< 0.001**
65–79	3761 (38.74)	2132 (56.69)	1629 (43.31)		
≥ 80	5947 (61.26)	1528 (25.69)	4419 (74.31)		
Residence, n (%)				χ^2=74.88	**<00.001**
Rural	4190 (43.16)	1375 (32.82)	2815 (67.18)		
Urban	5518 (56.84)	2285 (41.41)	3233 (58.59)		
Living arrangement, n (%)				χ^2=3.58	0.058
Living with family	8099 (83.43)	3087 (38.12)	5012 (61.88)		
Other	1609 (16.57)	573 (35.61)	1036 (64.39)		
Education, n (%)				χ^2=742.20	**< 0.001**
0	4488 (46.23)	1102 (24.55)	3386 (75.45)		
1–6	3292 (33.91)	1422 (43.20)	1870 (56.80)		
> 6	1928 (19.86)	1136 (58.92)	792 (41.08)		
Marital status, n (%)				χ^2=556.14	**<00.001**
Unmarried	5463 (56.27)	1501 (27.48)	3962 (72.52)		
Married	4245 (43.73)	2159 (50.86)	2086 (49.14)		
Economic situation, n (%)				χ^2=48.54	**< 0.001**
Good	979 (10.08)	287 (29.32)	692 (70.68)		
Average	6796 (70.00)	2551 (37.54)	4245 (62.46)		
Bad	1933 (19.91)	822 (42.52)	1111 (57.48)		
Work, n (%)				χ^2=39.57	**<00.001**
Other	2308 (23.77)	998 (43.24)	1310 (56.76)		
Manual labor	7400 (76.23)	2662 (35.97)	4738 (64.03)		
Smoking, n (%)				χ^2=0.83	0.361
No	8151 (83.96)	3057 (37.50)	5094 (62.50)		
Yes	1557 (16.04)	603 (38.73)	954 (61.27)		
Drinking, n (%)				χ^2=35.09	**<00.001**
No	8237 (84.85)	3004 (36.47)	5233 (63.53)		
Yes	1471 (15.15)	656 (44.60)	815 (55.40)		
Exercise, n (%)				χ^2=190.37	**< 0.001**
No	6371 (65.63)	2089 (32.79)	4282 (67.21)		
Yes	3337 (34.37)	1571 (47.08)	1766 (52.92)		
Cooking fuel, n (%)				χ^2=79.51	**< 0.001**
Other	5966 (61.45)	2042 (34.23)	3924 (65.77)		
Renewable energy sources	3742 (38.55)	1618 (43.24)	2124 (56.76)		
Cooking ventilation, n (%)				χ^2=17.65	**< 0.001**
No	868 (8.94)	270 (31.11)	598 (68.89)		
Yes	8840 (91.06)	3390 (38.35)	5450 (61.65)		
Life satisfaction, n (%)				χ^2=11.65	**0.003**
Good	6871 (70.78)	2649 (38.55)	4222 (61.45)		
Average	2553 (26.30)	926 (36.27)	1627 (63.73)		
Bad	284 (2.93)	85 (29.93)	199 (70.07)		
Self-rated health, n (%)				χ^2=15.53	**<00.001**
Good	4627 (47.66)	1826 (39.46)	2801 (60.54)		
Average	3769 (38.82)	1390 (36.88)	2379 (63.12)		
Bad	1312 (13.51)	444 (33.84)	868 (66.16)		
Hypertension, n (%)				χ^2=253.39	**< 0.001**
No	5459 (56.23)	1681 (30.79)	3778 (69.21)		
Yes	4249 (43.77)	1979 (46.58)	2270 (53.42)		
Diabetes, n (%)				χ^2=142.50	**<00.001**
No	8363 (86.15)	2956 (35.35)	5407 (64.65)		
Yes	1345 (13.85)	704 (52.34)	641 (47.66)		
Heart disease, n (%)				χ^2=68.14	**< 0.001**
Continued					

Variables	Total ($n=9708$)	Without LMM ($n=3660$)	With LMM ($n=6048$)	Statistic	*P*
No	7888 (81.25)	2820 (35.75)	5068 (64.25)		
Yes	1820 (18.75)	840 (46.15)	980 (53.85)		
Dementia, n (%)				χ^2=0.61	0.436
No	9418 (97.01)	3557 (37.77)	5861 (62.23)		
Yes	290 (2.99)	103 (35.52)	187 (64.48)		
Insurance, n (%)				χ^2=0.12	0.732
No	9011 (92.82)	3393 (37.65)	5618 (62.35)		
Yes	697 (7.18)	267 (38.31)	430 (61.69)		
$PM_{2.5}$, n (%)				χ^2=3.14	0.370
Quartile 1	2128 (21.92)	803 (37.73)	1325 (62.27)		
Quartile 2	1583 (16.31)	622 (39.29)	961 (60.71)		
Quartile 3	2913 (30.01)	1104 (37.90)	1809 (62.10)		
Quartile 4	3084 (31.77)	1131 (36.67)	1953 (63.33)		
NO_2, n (%)				χ^2=4.33	0.228
Quartile 1	2003 (20.63)	775 (38.69)	1228 (61.31)		
Quartile 2	1981 (20.41)	757 (38.21)	1224 (61.79)		
Quartile 3	2925 (30.13)	1117 (38.19)	1808 (61.81)		
Quartile 4	2799 (28.83)	1011 (36.12)	1788 (63.88)		

Table 1. Comparison of muscle mass in different basic characteristics of included participants. χ^2: Chi-square test, *LMM* low muscle mass. Significant values are in bold.

sarcopenia and muscle mass[12,14]. The pathophysiological mechanisms of muscle mass and sarcopenia are intricate and encompass interactions among multiple physiological systems. Possible explanations include alterations in skeletal muscle structure, myofascial dysfunction, muscle balance and resistance to growth, inflammation and impairment of mitochondrial function, as well as neural pathways, which mainly manifested as a decrease in muscle mass leading to the decline of muscle strength and worsens with age[1]. $PM_{2.5}$ can modulate inflammation in visceral adipose tissue, lipid metabolism in the liver, and glucose utilisation in skeletal muscle occurs through both CCR2-dependent and CCR2-independent pathway[40]. The signalling of neurotransmitters and neurotrophic factors, neuronal remodelling, and neurodegeneration are impaired by inflammation and oxidative stress induced by air pollution[41]. Breathing under normobaric conditions attenuated carbon monoxide-induced decreases in muscle oxygenation, particularly in the intercostal muscles, without affecting endurance[42]. In conclusion, air pollution can affect muscle through different pathways and comorbidities. Previous articles have highlighted the effects of air pollutants from solid fuels used for indoor cooking and domestic heat production on sarcopenia[43,44]. It follows that older people who rely on solid fuels for cooking and heating should prioritise ventilation to mitigate the adverse effects of fuel pollutants on muscle health.

Our study showed a significant correlation between an increase in IVF in spring and autumn and a reduced likelihood of developing LMM in older adults. Many studies have reported that air quality is associated with seasonal changes in air pollutants such as PM, CO and airborne microorganisms[45,46]. Seasonal climate-induced changes in temperature, humidity, etc., and accompanying differences in airborne particulate matter, microorganisms, etc., may be influential factors in the seasonal differences in the incidence of LMM. A survey of window opening behaviour in hospital wards showed that the lower frequency of window opening in summer and winter might be due to higher or lower outdoor temperatures, whereas, in the transition season, outdoor temperatures of 20 to 25 degrees are likely to be the most comfortable, with a correspondingly higher frequency of window opening. The humidity of the outdoor air in each season is also an essential factor influencing the frequency of window openings[47]. In addition, the results of a study investigating the effects of climate change on the infiltration of outdoor air pollution showed a clear seasonal pattern of particulate matter (PM) infiltration. Specifically, homes measured during transitional seasons, such as spring and autumn, had higher mean PM infiltration rates compared to homes measured during summer and winter[48], which may explain the association between IVF and LMM being significant in spring and autumn rather than summer and winter .

Subgroup analyses showed that adjusted covariates were not significant modifiers of the association between IVF and LMM, but we still observed significant interactions between drinking and the association between IVF and LMM. We observed a significant association of IVF with LMM in men but not women.Previous studies have reported sex differences in muscle homeostasis[49,50].Sex steroids promote muscle function and benefit skeletal muscle repair and metabolic function after injury. Androgens may be the main sex steroid regulating muscle homeostasis in men[51], which may potentially account for the sex differences in LMM and IVF observed in this study. Previous studies have confirmed that muscle mass decreases with age[52], however, our study found that the association between IVF and LMM showed significant age heterogeneity: a significant negative correlation was observed in the 65–79 year old group, whereas no statistically significant correlation was observed in the ≥80 year old group. This may be due to the severe loss of muscle mass due to multiple pathophysiological mechanisms in advanced age individuals, when the effects of IVF are masked by the systemic aging process. In our study, we observed that in cities, IVF was significantly associated with LMM, which may be due to denser

Variables	Total (*n* = 9708)	Low IVF (*n* = 856)	Intermediate IVF (*n* = 3121)	High IVF (*n* = 5731)	Statistic	*P*
Gender, n (%)					χ^2=10.11	**0.006**
Female	5271 (54.30)	505 (9.58)	1710 (32.44)	3056 (57.98)		
Male	4437 (45.70)	351 (7.91)	1411 (31.80)	2675 (60.29)		
Age, n (%)					χ^2=34.51	**< 0.001**
65–79	3761 (38.74)	256 (6.81)	1194 (31.75)	2311 (61.45)		
≥80	5947 (61.26)	600 (10.09)	1927 (32.40)	3420 (57.51)		
Residence, n (%)					χ^2=144.05	**< 0.001**
Rural	4190 (43.16)	483 (11.53)	1502 (35.85)	2205 (52.63)		
Urban	5518 (56.84)	373 (6.76)	1619 (29.34)	3526 (63.90)		
Living arrangement, n (%)					χ^2=64.12	**< 0.001**
Living with family	8099 (83.43)	634 (7.83)	2596 (32.05)	4869 (60.12)		
Other	1609 (16.57)	222 (13.80)	525 (32.63)	862 (53.57)		
Education, n (%)					χ^2=197.07	**< 0.001**
0	4488 (46.23)	550 (12.25)	2387 (53.19)	1551 (34.56)		
1–6	3292 (33.91)	233 (7.08)	2046 (62.15)	1013 (30.77)		
>6	1928 (19.86)	73 (3.79)	1298 (67.32)	557 (28.89)		
Marital status, n (%)					χ^2=26.86	**< 0.001**
Unmarried	5463 (56.27)	553 (10.12)	1745 (31.94)	3165 (57.94)		
Married	4245 (43.73)	303 (7.14)	1376 (32.41)	2566 (60.45)		
Economic situation, n (%)					χ^2=96.33	**< 0.001**
Good	979 (10.08)	141 (14.40)	532 (54.34)	306 (31.26)		
Average	6796 (70.00)	634 (9.33)	3962 (58.30)	2200 (32.37)		
Bad	1933 (19.91)	81 (4.19)	1237 (63.99)	615 (31.82)		
Work, n (%)					χ^2=29.74	**< 0.001**
Other	2308 (23.77)	146 (6.33)	714 (30.94)	1448 (62.74)		
Manual labor	7400 (76.23)	710 (9.59)	2407 (32.53)	4283 (57.88)		
Smoking, n (%)					χ^2=7.93	**0.019**
No	8151 (83.96)	743 (9.12)	2637 (32.35)	4771 (58.53)		
Yes	1557 (16.04)	113 (7.26)	484 (31.09)	960 (61.66)		
Drinking, n (%)					χ^2=5.99	0.050
No	8237 (84.85)	745 (9.04)	2667 (32.38)	4825 (58.58)		
Yes	1471 (15.15)	111 (7.55)	454 (30.86)	906 (61.59)		
Exercise, n (%)					χ^2=180.96	**< 0.001**
No	6371 (65.63)	649 (10.19)	2268 (35.60)	3454 (54.21)		
Yes	3337 (34.37)	207 (6.20)	853 (25.56)	2277 (68.23)		
Cooking fuel, n (%)					χ^2=181.61	**< 0.001**
Other	5966 (61.45)	655 (10.98)	2082 (34.90)	3229 (54.12)		
Renewable energy sources	3742 (38.55)	201 (5.37)	1039 (27.77)	2502 (66.86)		
Cooking ventilation, n (%)					χ^2=374.09	**< 0.001**
No	868 (8.94)	222 (25.58)	310 (35.71)	336 (38.71)		
Yes	8840 (91.06)	634 (7.17)	2811 (31.80)	5395 (61.03)		
Life satisfaction, n (%)					χ^2=109.76	**< 0.001**
Good	6871 (70.78)	503 (7.32)	4226 (61.50)	2142 (31.17)		
Average	2553 (26.30)	300 (11.75)	1352 (52.96)	901 (35.29)		
Bad	284 (2.93)	53 (18.66)	153 (53.87)	78 (27.46)		
Self-rated health, n (%)					χ^2=42.68	**< 0.001**
Good	4627 (47.66)	346 (7.48)	2848 (61.55)	1433 (30.97)		
Average	3769 (38.82)	350 (9.29)	2172 (57.63)	1247 (33.09)		
Bad	1312 (13.51)	160 (12.20)	711 (54.19)	441 (33.61)		
Hypertension, n (%)					χ^2=0.16	0.922
No	5459 (56.23)	484 (8.87)	1762 (32.28)	3213 (58.86)		
Yes	4249 (43.77)	372 (8.76)	1359 (31.98)	2518 (59.26)		
Diabetes, n (%)					χ^2=2.95	0.229
No	8363 (86.15)	724 (8.66)	2709 (32.39)	4930 (58.95)		
Yes	1345 (13.85)	132 (9.81)	412 (30.63)	801 (59.55)		
Heart disease, n (%)					χ^2=1.25	0.535
Continued						

Variables	Total (n = 9708)	Low IVF (n = 856)	Intermediate IVF (n = 3121)	High IVF (n = 5731)	Statistic	P
No	7888 (81.25)	704 (8.92)	2547 (32.29)	4637 (58.79)		
Yes	1820 (18.75)	152 (8.35)	574 (31.54)	1094 (60.11)		
Dementia, n (%)					χ^2=3.15	0.207
No	9418 (97.01)	822 (8.73)	3030 (32.17)	5566 (59.10)		
Yes	290 (2.99)	34 (11.72)	91 (31.38)	165 (56.90)		
Insurance, n (%)					χ^2=12.46	**0.002**
No	9011 (92.82)	782 (8.68)	2937 (32.59)	5292 (58.73)		
Yes	697 (7.18)	74 (10.62)	184 (26.40)	439 (62.98)		
$PM_{2.5}$, n (%)					χ^2=3.06	0.802
Quartile 1	2128 (21.92)	188 (8.83)	676 (31.77)	1264 (59.40)		
Quartile 2	1583 (16.31)	151 (9.54)	491 (31.02)	941 (59.44)		
Quartile 3	2913 (30.01)	243 (8.34)	957 (32.85)	1713 (58.81)		
Quartile 4	3084 (31.77)	274 (8.88)	997 (32.33)	1813 (58.79)		
NO_2, n (%)					χ^2=21.02	**0.002**
Quartile 1	2003 (20.63)	195 (9.74)	639 (31.90)	1169 (58.36)		
Quartile 2	1981 (20.41)	149 (7.52)	585 (29.53)	1247 (62.95)		
Quartile 3	2925 (30.13)	269 (9.20)	941 (32.17)	1715 (58.63)		
Quartile 4	2799 (28.83)	243 (8.68)	956 (34.16)	1600 (57.16)		

Table 2. Comparison of indoor ventilation frequency in different basic characteristics of included participants. χ^2: Chi-square test, *IVF* indoor ventilation frequency. Significant values are in bold.

Variables	Total (n = 9708)	Without LMM (n = 3660)	With LMM (n = 6048)	Statistic	P
Spring ventilation frequency, n (%)				χ^2=14.442	< 0.001
0 time/week	418 (4.30)	105 (25.12)	313 (74.88)		
1–5 times/week	3776 (38.90)	1380 (36.55)	2396 (63.45)		
>5 times/week	5514 (56.80)	2175 (39.45)	3339 (60.55)		
Summer ventilation frequency, n (%)				χ^2=33.664	< 0.001
0 time/week	239 (2.46)	55 (23.01)	184 (76.99)		
1–5 times/week	2089 (21.52)	730 (34.94)	1359 (65.06)		
>5 times/week	7380 (76.02)	2875 (38.96)	4505 (61.04)		
Autumn ventilation frequency, n (%)				χ^2=116.851	< 0.001
0 time/week	370 (3.81)	80 (21.62)	290 (78.38)		
1–5 times/week	3734 (38.46)	1394 (37.33)	2340 (62.67)		
>5 times/week	5604 (57.73)	2186 (39.01)	5604 (60.99)		
Winter ventilation frequency, n (%)				χ^2=33.148	< 0.001
0 time/week	1939 (19.97)	626 (32.28)	1313 (67.72)		
1–5 times/week	4026 (41.47)	1536 (38.15)	2490 (61.85)		
>5 times/week	3743 (38.56)	1498 (40.02)	2245 (59.98)		
Overall ventilation, n (%)				χ^2=44.778	< 0.001
0–3 (low)	856 (8.82)	236 (27.57)	620 (72.43)		
4–5 (intermediate)	3121 (32.15)	1165 (37.33)	1956 (62.67)		
6–8 (high)	5731 (59.03)	2259 (39.42)	3472 (60.58)		

Table 3. Bivariate association between seasonal indoor ventilation frequency and low muscle mass. χ^2: Chi-square test, *LMM* low muscle mass.

buildings and poorer air quality in cities, where ventilation can more significantly improve indoor air quality. Yin J et al. also observed a significant difference in the importance of ventilation for public health between urban and rural areas, influenced by factors such as building density and height[53] .Smoking impacts cellular-level muscle proteolysis, leading to impaired muscle mass and the increased demand for indoor ventilation to mitigate indoor air pollutants[54,55]. We observed a significant correlation between IVF and LMM in the non-smoking group, which may be due to the fact that smoke and toxins produced by smoking are more damaging to muscle mass, which is not achieved by improving indoor ventilation. This may suggest that smoking cessation is more effective in protecting muscle mass than ventilation. Previous studies have established physical exercise as a protective factor against sarcopenia, demonstrating its efficacy in preserving muscle mass and strength[56,57].

IVF	Model 1	Model 2	Model 3
	OR (95% CI)		
Low IVF	Ref.	Ref.	Ref.
Intermediate IVF	0.639 (0.541,0.755)***	0.793 (0.662,0.950)*	0.805 (0.669,0.969)*
High IVF	0.585 (0.499,0.686)***	0.818 (0.687,0.975)*	0.818 (0.684,0.979)*

Table 4. Association between indoor ventilation frequency and low muscle mass. *IVF* indoor ventilation frequency, *OR* odds ratio, *CI* confidence interval, *$P<0.05$, ***$P<0.001$. Model 1: No variables adjusted, Model 2: Adjusted for gender, age, residence, living arrangement, education, marital status, economic situation, work, smoking, drinking, exercise, cooking fuel, cooking ventilation. Model 3: Further adjusted for life satisfaction, self-rated health, hypertension, diabetes, heart disease, dementia, insurance, $PM_{2.5}$, NO_2.

Season[a]	Low IVF	Intermediate IVF	High IVF
	OR (95% CI)		
Spring	Ref.	0.747 (0.581,0.961)*	0.767 (0.597,0.985)*
Summer	Ref.	0.788 (0.561,1.108)	0.730 (0.524,1.016)
Autumn	Ref.	0.625 (0.474,0.824)***	0.659 (0.501,0.868)**
Winter	Ref.	0.936 (0.824,1.064)	0.956 (0.839,1.090)

Table 5. Association between seasonal indoor ventilation frequency and low muscle mass. *OR* odds ratio, *CI* confidence interval, *$P<0.05$, **$P<0.01$, ***$P<0.001$. [a]Model 3: Adjusted for gender, age, residence, living arrangement, education, marital status, economic situation, work, smoking, drinking, exercise, cooking fuel, cooking ventilation, life satisfaction, self-rated health, hypertension, diabetes, heart disease, dementia, insurance, $PM_{2.5}$,NO_2.

Our study further revealed a significant association between increased IVF and LMM specifically within the physically active subgroup, suggesting potential synergistic effects between exercise and optimized ventilation in muscle preservation. This finding warrants further investigation into whether exercise intensity and modality (e.g., resistance training vs. aerobic exercise) differentially modulate the protective benefits of IVF against LMM. Notably, the association between IVF and LMM was exclusively observed in individuals with favorable self-rated health status and absence of chronic comorbidities (hypertension, diabetes, cardiovascular disease, or dementia). Older adults with poor health status or chronic conditions often experience prolonged health deterioration that may lead to advanced muscle atrophy or metabolic dysregulation, potentially obscuring ventilation-related effects. Furthermore, chronic disease patients, particularly elderly or long-term sufferers, frequently exhibit diminished physiological adaptability and recovery capacity. Their muscle mass is typically compromised by disease progression or pharmacological interventions (e.g., corticosteroid use), which may attenuate ventilation-mediated impacts on musculoskeletal health. Our analysis identified a significant protective effect of IVF against LMM under elevated NO2 concentrations. Airborne pollutants including PM2.5 and NO2 have been shown to induce mitochondrial dysfunction through increased reactive oxygen species production and pro-inflammatory cascades[58,59]. Enhanced ventilation during high NO2 exposure may mitigate these effects through improved air exchange, thereby reducing pollutant concentrations and demonstrating measurable protection - an effect less apparent under low pollution conditions. Additionally, we observed significant IVF-LMM associations and notable interaction effects with alcohol consumption status in drinking populations. Extensive evidence documents alcohol's detrimental impacts on muscle integrity through multiple pathways, including dysregulated autophagy, mitochondrial impairment, and nutrient malabsorption[60,61]. Compared to abstainers, alcohol consumers exhibited higher smoking prevalence and prolonged indoor exposure due to social habits or health limitations (e.g., chronic disease-related mobility restrictions), potentially amplifying ventilation sensitivity. Conversely, non-drinkers likely represent a health-conscious cohort (evidenced by balanced nutrition and regular exercise) whose muscle mass appears less susceptible to ventilation variations. However, our analysis was constrained by the database's lack of alcohol consumption frequency/dosage metrics, precluding dose-response assessment and introducing potential residual confounding. Future investigations should incorporate standardized alcohol biomarkers (e.g., phosphatidylethanol) and detailed consumption patterns to elucidate alcohol-ventilation synergies.

Conclusions

This study examined the relationship between overall and seasonal IVF and LMM in Chinese older adults.The findings suggest that higher IVF is significantly associated with lower occurrence of LMM in Chinese older adults, especially in the Spring and Autumn seasons. This study provides valuable insights to promote successful aging and reduce the burden of LMM in the elderly population.

Subgroup	n (%)	OR (95%CI)	P	P for interaction
Gender				0.971
Female	5,271 (54.30)	0.97 (0.94 ~ 1.01)	0.103	
Male	4,437 (45.70)	0.96 (0.93 ~ 0.99)	0.020	
Age				0.703
65-79	3,761 (38.74)	0.96 (0.93 ~ 1.00)	0.032	
≥80	5947 (61.26)	0.97 (0.94 ~ 1.00)	0.088	
Residence				0.977
Rural	4,190 (43.16)	0.97 (0.93 ~ 1.00)	0.066	
Urban	5,518 (56.84)	0.97 (0.94 ~ 1.00)	0.048	
Living arrangement				0.740
Living with family	8,099 (83.43)	0.97 (0.94 ~ 0.99)	0.009	
Other	1,609 (16.57)	0.97 (0.93 ~ 1.03)	0.318	
Education				0.929
0	4,488 (46.23)	0.98 (0.95 ~ 1.02)	0.270	
1-6	3,292 (33.91)	0.98 (0.94 ~ 1.01)	0.228	
>6	1,928 (19.86)	0.97 (0.92 ~ 1.02)	0.237	
Marital status				0.141
Unmarried	5,463 (56.27)	0.99 (0.96 ~ 1.02)	0.392	
Married	4,245 (43.73)	0.95 (0.91 ~ 0.98)	0.001	
Economic situation				0.381
Good	979 (10.08)	1.00 (0.94 ~ 1.07)	0.912	
Average	6,796 (70.00)	0.96 (0.94 ~ 0.99)	0.010	
Bad	1,933 (19.91)	0.97 (0.92 ~ 1.03)	0.361	
Work				0.319
Other	2,308 (23.77)	0.94 (0.90 ~ 0.99)	0.022	
Manual labor	7,400 (76.23)	0.98 (0.95 ~ 1.00)	0.063	
Smoking				0.486
No	8,151 (83.96)	0.97 (0.94 ~ 0.99)	0.007	
Yes	1,557 (16.04)	0.99 (0.93 ~ 1.04)	0.619	
Drinking				0.015
No	8,237 (84.85)	0.98 (0.96 ~ 1.01)	0.128	
Yes	1,471 (15.15)	0.90 (0.85 ~ 0.96)	<.001	
Exercise				0.056
No	6,371 (65.63)	0.99 (0.96 ~ 1.01)	0.317	
Yes	3,337 (34.37)	0.93 (0.90 ~ 0.97)	<.001	
Cooking fuel				0.897
Other	5,966 (61.45)	0.97 (0.94 ~ 1.00)	0.064	
Renewable energy sources	3,742 (38.55)	0.98 (0.94 ~ 1.02)	0.282	
Cooking ventilation				0.898
No	868 (8.94)	0.97 (0.90 ~ 1.03)	0.337	
Yes	8,840 (91.06)	0.97 (0.95 ~ 1.00)	0.038	
Life satisfaction				0.313
Good	6,871 (70.78)	0.97 (0.94 ~ 1.00)	0.031	
Average	2,553 (26.30)	0.97 (0.93 ~ 1.01)	0.132	
Bad	284 (2.93)	1.05 (0.93 ~ 1.18)	0.454	
Self-rated health				0.096
Good	4,627 (47.66)	0.95 (0.91 ~ 0.98)	0.002	
Average	3,769 (38.82)	0.98 (0.95 ~ 1.02)	0.421	
Bad	1,312 (13.51)	1.01 (0.95 ~ 1.07)	0.787	
Hypertension				0.310
No	5,459 (56.23)	0.96 (0.93 ~ 0.99)	0.012	
Yes	4,249 (43.77)	0.98 (0.95 ~ 1.01)	0.238	
Diabetes				0.549
No	8,363 (86.15)	0.97 (0.95 ~ 1.00)	0.028	
Yes	1,345 (13.85)	0.96 (0.91 ~ 1.02)	0.195	
Heart disease				0.240
No	7,888 (81.25)	0.96 (0.94 ~ 0.99)	0.004	
Yes	1,820 (18.75)	0.99 (0.94 ~ 1.05)	0.844	
Dementia				0.923
No	9,418 (97.01)	0.97 (0.95 ~ 0.99)	0.010	
Yes	290 (2.99)	0.93 (0.81 ~ 1.06)	0.258	
Insurance				0.380
No	9,011 (92.82)	0.97 (0.95 ~ 1.00)	0.020	
Yes	697 (7.18)	0.94 (0.86 ~ 1.03)	0.167	
PM2 5				0.824
Quartile 1	2,128 (21.92)	0.96 (0.91 ~ 1.01)	0.111	
Quartile 2	1,583 (16.31)	0.96 (0.91 ~ 1.02)	0.178	
Quartile 3	2,913 (30.01)	0.97 (0.93 ~ 1.01)	0.163	
Quartile 4	3,084 (31.77)	0.98 (0.94 ~ 1.02)	0.413	
NO2				0.080
Quartile 1	2,003 (20.63)	0.99 (0.94 ~ 1.04)	0.642	
Quartile 2	1,981 (20.41)	1.02 (0.97 ~ 1.08)	0.390	
Quartile 3	2,925 (30.13)	0.94 (0.90 ~ 0.98)	0.005	
Quartile 4	2,799 (28.83)	0.95 (0.91 ~ 0.99)	0.022	

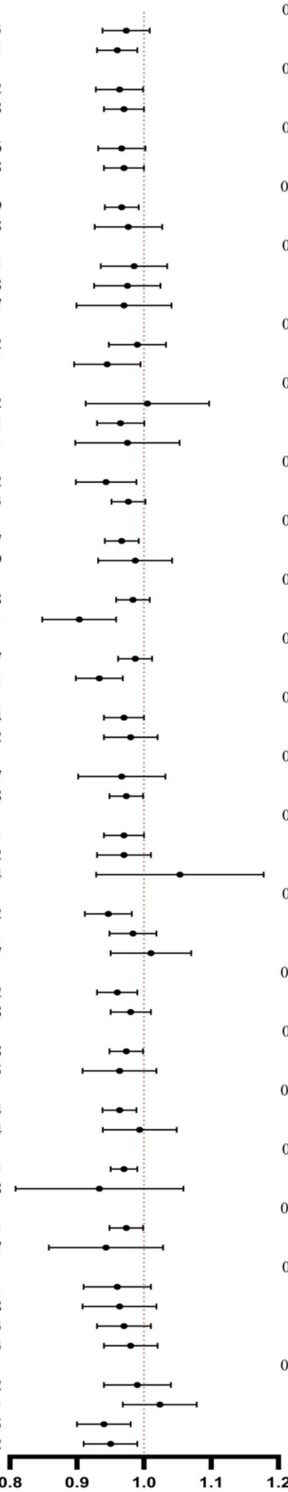

Fig. 2. ORs and 95% CI for low muscle mass in adherence to indoor ventilation frequency, stratified by selected characteristics.

Limitation

The current study is subject to several limitations. Firstly, as our data is derived from a national cross-sectional study that precludes the establishment of causal relationships, it is imperative to examine the interplay between IVF and LMM. Further extension of follow-up is necessary to assess the longitudinal relationship between IVF and muscle decline in older adults and to determine the causal link between these two factors. Secondly, this study exclusively examines the impact of the window opening on LMM across seasons without considering other ventilation systems, such as air conditioners and air purifiers, and neglects the influence of specific ventilation locations, the area of open windows and the duration of each ventilation session. Third, this study investigated the association between IVF and LMM in different seasons, but the questionnaire content limitations prevented the determination of muscle mass in each season.We plan to refine the seasonal tracking design in future studies to more fully reveal the relationship between LMM and IVF. Fourth, the present study assumes an ideal scenario in which indoor air quality can be enhanced through indoor ventilation; however, pollutants from the outdoor environment and adverse weather conditions may exacerbate indoor air pollution. Hence, additional research is required to explore the underlying mechanisms of the influence of window opening and ventilation on muscle mass in older individuals.

Data availability

The data of CLHLS are available at https://opendata.pku.edu.cn/dataverse/CHADS.

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Author contributions
Each author has met the authorship requirements. JW and YL wrote the main manuscript text. JT organized the data, and JW completed all data analysis. XX and ZW reviewed the manuscript and revised it. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Institutional review board statement
The study was conducted according to the guidelines of the Declaration of Helsinki and approved by Peking University's Ethics Committee (IRB00001052-13074).

Informed consent
Informed consent was obtained from all subjects involved in the study.

Additional information

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