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RESEARCH

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Association between urbanization levels and frailty among middle-aged and older adults in China: evidence from the CHARLS

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Abstract

Background Rapid urbanization is underway in China. However, the impact of urbanization on frailty remains unclear. This study aims to investigate the relationship between urbanization and frailty among middle-aged and older adults.

Methods We analyzed nationally representative data from the China Health and Retirement Longitudinal Study (CHARLS) spanning 2011 to 2018. After applying inclusion and exclusion criteria, 10,758 non-frail individuals at baseline were analyzed. The exposure of interest was the comprehensive urbanization level. Urbanization level (0.072–0.689) was assessed using the entropy method. Frailty was assessed using the frailty index (FI), which ranges from 0 to 100. Frailty was defined as FI ≥ 25, and the urbanization–frailty association was assessed using - the restricted cubic spline (RCS) expressions and Cox proportional hazards models. Least absolute shrinkage and selection operator (LASSO) regression were employed to evaluate major factors associated with frailty.

Results The results revealed a U-shaped nonlinear association between urbanization level and frailty incidence, with a turning point at 0.3 ($P_{nonlinear} < 0.001$). In the Cox model, for urbanization scores below 0.3, each ten-percentile increase was associated with an HR of 0.871 (95% CI 0.843–0.900, $P < 0.05$). Conversely, scores at or above 0.3 had an HR of 1.178 (95% CI 1.053–1.319, $P < 0.05$) per ten-percentile increase. In the subgroup analysis of participants with urbanization scores below 0.3, there was a significant interaction between current work status and subgroups with dyslipidemia. LASSO regression showed that, for urbanization scores < 0.3, total retail sales (coefficient = −0.129) and per capita income (coefficient = −0.071) were most protective against frailty. For scores ≥ 0.3, key urbanization factors associated with increased frailty risk included the number of college students per 10,000 people (coefficient = 0.080) and the proportion of built-up land in the urban area (coefficient = 0.060).

Conclusions Urbanization level had U-shaped association with frailty incidence. Factors such as total retail sales of consumer goods per capita, per capita disposable income of urban residents, and the number of college students per 10,000 people may be key in formulating a strategy for frailty prevention.

Keywords Urbanization, Frailty, Incidence, Nonlinear relationship, CHARLS

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Background

According to the 2018 Revision of World Urbanization Prospects and World Urbanization Trends 2018 [1, 2], the global urbanization rate increased from 24% in 1950 to 55% in 2018, with North America at 82% and Africa at 43%. By 2050, 68% of the global population is projected to live in urban areas, driven mainly by growth in low- and middle-income countries [1]. As the largest low- and middle-income country, China has experienced rapid urbanization since its reform and opening-up policies, with its urbanization rate rising from 17.9% in 1978 to 60.6% in 2019 [2]. While urbanization has improved aspects such as personal income, education, access to healthcare, and infrastructure [3–5], it has also introduced challenges, including inequalities in public health services, reduced living space, environmental pollution, and sedentary lifestyles [2, 6–8]. These factors contribute to frailty, a condition linked to adverse outcomes such as disability, cognitive decline, and increased mortality [9–12]. With China experiencing rapid population aging, frailty has become a significant public health burden. Understanding the relationship between urbanization and frailty among middle-aged and older adults is crucial for developing targeted strategies to mitigate frailty risk amid ongoing urbanization and demographic shifts.

To date, researchers have utilized various indicators, such as urban–rural dichotomy [4], nighttime light index [13], population density [14], and gross domestic product (GDP) [15], to evaluate urbanization levels. While the urban–rural dichotomy allows for clear comparisons between urban and rural health outcomes, this simplistic binary approach fails to capture the overlapping and complex factors affecting health during urbanization [16]. For example, a cross-sectional study conducted in China [17] used indicators such as the proportion of urban built-up areas, GDP per capita, population density, and hospital beds per thousand people to evaluate urban–rural land use transformation, economic growth, population concentration, and healthcare service levels, exploring their relationship with self-rated health. Similarly, Wang et al. constructed a composite urbanization index combining nighttime light intensity, population density, GDP, and the proportion of non-agricultural activities at the county level [18]. Although these composite indices reflect urbanization from multiple perspectives, they often focus on singular aspects of urban development, emphasizing the quantity and scale of cities while neglecting development quality and environmental costs [19].

In response to the limitations of previous studies, some research has shifted toward multi-indicator evaluation methods that incorporate various dimensions such as population, economy, society, space, and environment when assessing urbanization levels. Cai et al. developed a comprehensive urbanization evaluation index based on four dimensions: demographic urbanization, economic urbanization, social urbanization, and spatial urbanization, enriching the concept of new urbanization [2]. However, studies examining the association between comprehensive urbanization and health outcomes remain scarce, primarily limited to cross-sectional studies on self-rated health. While self-rated health can partially reflect health status, it lacks objective evaluation standards and reliability. Existing evidence has primarily focused on the individual level, indicating an association between socioeconomic status and frailty risk [3, 20]. Limited studies have explored the relationship between socioeconomic factors, such as gross GDP per capita, purchasing power parity (PPP), per capita healthcare expenditure, and frailty prevalence in communities [21]. Nevertheless, at the societal level, evidence linking social factors to frailty remains insufficient [20].

Based on previous studies, we hypothesized that urbanization levels are nonlinearly associated with frailty risk, potentially characterized by a U-shaped relationship. First, we developed a comprehensive urbanization assessment framework utilizing statistical yearbook data from various Chinese cities. Additionally, we constructed a frailty index (FI) to objectively assess frailty risk based on cohort data from the China Health and Retirement Longitudinal Study (CHARLS). Second, urbanization levels were quantified using an entropy-based score derived from 19 multidimensional indicators encompassing demographic, economic, social, and spatial dimensions. Third, the Cox proportional hazards models and restricted cubic splines (RCS) were employed to examine the hypothesized U-shaped relationship, identifying the optimal threshold for subsequent linear transformations. Lastly, Least absolute shrinkage and selection operator (LASSO) regression was applied to identify key urbanization variables significantly associated with frailty risk. These findings provide a robust analytical framework and actionable insights for targeted interventions to mitigate frailty risks among middle-aged and older adults amidst rapid urbanization and population aging.

Methods

Study design and population

This study utilized data from the CHARLS, a nationally representative longitudinal cohort survey conducted between 2011 and 2020 to evaluate residents' social, economic, and health status [22]. The baseline survey of the CHARLS, conducted between June 2011 and March 2012, included 10,257 households and 17,708 participants [22]. Participants were followed up every 2 years through face-to-face interviews using standardized questionnaires. CHARLS implemented a multistage probability sampling design to ensure representativeness and reduce potential bias. Sampling was performed at four levels: county (or district), village (or community), household, and individual. Specifically, stratified sampling and probability proportional to size (PPS) sampling techniques were employed to randomly select 150 counties or districts and 450 villages or communities across 28 provinces. PPS sampling was applied at the county/district and village/community stages. From survey design to data collection, CHARLS implemented stringent quality control measures to ensure data accuracy and reliability. Among these, the Computer-Assisted Personal Interviewing system (CAPI) system allowed for the timely identification and correction of interviewer misconduct. Additionally, in each follow-up wave, interviewers revisited households that had not responded in the previous survey wave, further improving response rates. These key measures, along with other quality assurance protocols, collectively enhanced the overall quality and representativeness of the data. Specifically, the response rates for waves 1 to 5 were 80.5%, 88.3%, 87.1%, 86.4%, and 86.8%, respectively. The CHARLS study was approved by the Institutional Review Board of Peking University and adhered to the principles outlined in the 1964 Declaration of Helsinki. Informed consent was obtained from all participants. This study's data and relevant information are publicly available for download from the CHARLS project website (http://charls.pku.edu.cn/).

Considering the potentially substantial impact of the COVID-19 pandemic on individual and urban development in the 2020 survey, this study utilized data from the first four waves of the CHARLS dataset (2011, 2013, 2015, and 2018). Participants were selected through the following steps. First, individuals with missing data on baseline urbanization assessment indicators ($n=3675$), those younger than 45 years ($n=448$), those with missing age information ($n = 10$), and those with missing data for more than 20% of the FI components ($n=181$) were excluded [21]. Second, participants identified as frail at baseline ($n=2142$) were excluded to ensure that the analysis focused on individuals without frailty at baseline. Third, participants lost to follow-up or with frailty status unavailable across all three follow-up waves (2013, 2015, and 2018; $n=494$) were excluded. Ultimately, a total of 10,758 participants were included in the final analysis. The participant selection process is illustrated in Fig. 1.

Evaluation and calculation of the urbanization index

The development of urbanization is a complex and dynamic process accompanied by changes in population, industry, society, space, ecology, and other multidimensional factors [23]. Recent trends in research have emphasized the construction of scientific and rational indicators to comprehensively assess the development status of urbanization within a given region

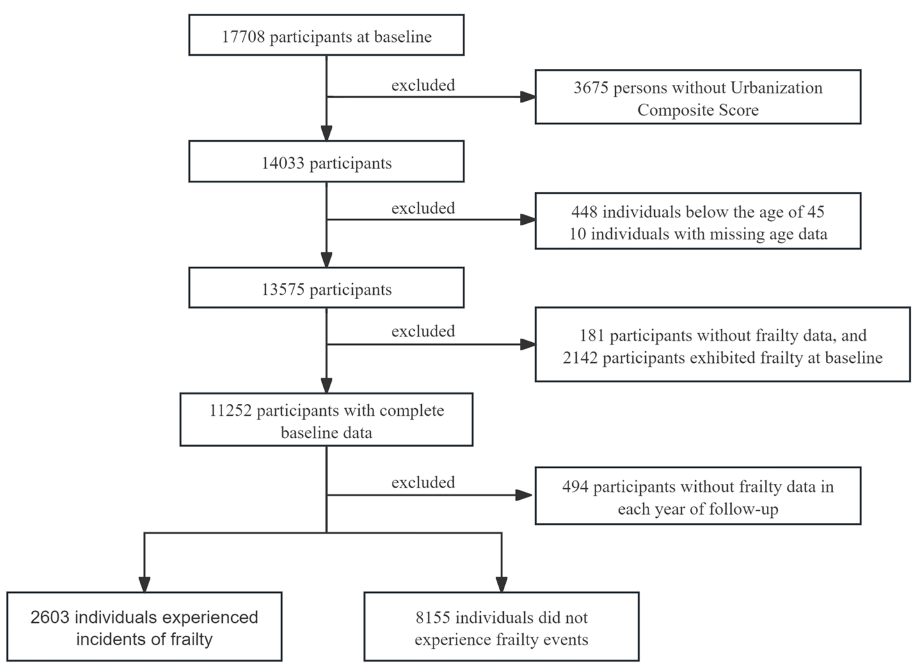

Fig. 1 Flow of participants in current CHARLS study

[24]. Drawing on this trend and existing research [25, 26], in this study, 19 indicators were selected from the four dimensions of economic, demographic, social, and spatial urbanization to comprehensively evaluate the level of urbanization (Additional file 1: Table S1), using data from wave 1 (2011) of the CHARLS database to calculate the baseline urbanization scores for each individual's city. Population urbanization serves as the foundation for urbanization development, with population concentration in cities as the fundamental driver of regional urbanization development. Economic urbanization represents the core aspect of urbanization development, with economic development as the driving force behind urbanization progress. Social urbanization indicates the spread of civilization and the level of people's living standards, enriching the essence of urbanization. Spatial urbanization constitutes a significant aspect of urbanization, as changes in land use structure and the development of transportation facilities directly reflect the level of urbanization construction [27].

This study utilizes the improved entropy weight method to assign weights to the indicators of the comprehensive urbanization evaluation system. The comprehensive weights of the urbanization evaluation system and the comprehensive urbanization scores for each city were calculated using the entropy weight method formula [28, 29]. This method avoids the influence of subjective factors inherent in subjective weighting methods and incorporates an assessment of indicator differences based on the entropy weight method, thereby enhancing the accuracy and realism of the evaluation results.

With m objects and n evaluation indicators, let a_{ij} denote the jth indicator value of the ith object. Given the differing dimensions of each indicator in the system, standardizing the original data is essential.

The processing method for standardizing all indicators is:

$$\overline{x}_{ij} = \frac{\alpha_{ij} - min(\alpha_{ij})}{max(\alpha_{ij}) - min(\alpha_{ij})} \tag{1}$$

Since the standardized indicator values may be zero after standardization, which is not conducive to subsequent calculations, this paper performs a coordinate transformation on the standardized indicator using the formula $x_{ij} = \overline{x}_{ij} + 0.0001$. Next, this paper calculates the proportion of the ith indicator value in the jth indicator:

$$p_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij} \tag{2}$$

The entropy of the jth indicator is calculated as follows:

$$e_j = -(\ln m)^{-1} \sum_{i=1}^{m} (p_{ij} \ln p_{ij}) \tag{3}$$

The weight of the jth indicator is calculated as follows:

$$w_j = (1 - e_j) / \sum_{j=1}^{m} (1 - e_j) \tag{4}$$

where $1 - e_j$ is the difference parameter of the jth indicator.

According to the above calculations, the comprehensive indicator of urbanization can be obtained as follows:

$$N\_\_Urban_i = \sum_{j=1}^{n} (w_j x_{ij})(i = 1,2,\cdots,m) \tag{5}$$

Assessment of frailty

Frailty was evaluated by the FI, which was calculated as the accumulation of age-related health deficits. We constructed and calculated the FI following standard procedures used in previous research [30, 31]. After screening the CHARLS data, 32 items were selected to construct the FI, encompassing variables related to comorbidity, physical function, disability, depression, and cognition (Additional file 1: Table S2). Each item, except for item 32, was dichotomized into 0 or 1 based on the responses to the questionnaire. A value of 0 indicated the absence of the deficit, while 1 indicated its presence. Item 32 was treated as a continuous variable ranging from 0 to 1, where a higher value denoted worse cognition. In this study, participants were excluded from scale analysis if they had missing values for more than 20% of the items on that scale [32]. For each participant, the 32-FI was calculated as the sum of present health deficits divided by 32 and multiplied by 100. Thus, the 32-FI was a continuous variable ranging from 0 to 100, with a higher value indicating a higher degree of frailty. Consistent with previous studies, frailty was defined as 32-FI $\geq$ 0.25 [31]. The 32-FI was calculated for each wave of CHARLS. Frailty progression was evaluated through repeated measurements of the FI.

Covariates

We selected a comprehensive set of potential confounders to analyze the association between urbanization and frailty, encompassing demographic, socioeconomic, early-life, psychosocial, health-related factors, and particulate matter 2.5 ($PM_{2.5}$). Socioeconomic covariates included current employment status (categorized as not working or working) and household consumption [33]. Early-life covariates included education level (classified as illiterate, primary school education or below, education below a bachelor's degree, and bachelor's degree or higher), first occupation, and health status during youth (categorized as excellent, very good, good, fair, or poor) [34, 35]. Covariates related to social support included marital status (categorized as non-married and married), family support (living with children, meeting children weekly, virtual weekly meetings with children, having children without support, and having no children or support), and participation in social activities [36, 37]. The health-related covariates included behavioral factors (drinking status: non-drinker or current drinker; smoking status: non-smoker or current smoker; public health insurance coverage), chronic disease factors (dyslipidemia, liver disease, kidney disease, and gastric or digestive diseases), and environmental exposure to $PM_{2.5}$ concentrations [33, 38, 39].

Youthful health status was defined based on participants' self-reported health condition before age 15. Family support was defined by the presence of offspring and the closeness of their relationships. Social activity was assessed by participating in ten activities over the past month, such as interacting with friends, playing Mahjong, or joining clubs. Engagement in at least one activity was considered social participation. The first job referred to the participant's self-reported initial occupation. BMI (Body mass index) was calculated as weight (kg) divided by height squared (m^2) and expressed in kg/m^2. Smoking status was classified as current, former, or never smoker, while alcohol consumption was defined as drinking at least once per month. Chronic conditions, including four disease categories, were identified based on participants' self-reported physician diagnoses (Additional file 1: Table S3). $PM_{2.5}$ exposure data was obtained from the 2011 $PM_{2.5}$ dataset within the China High Air Pollution (CHAP) data series. Data on the first job and youthful health status were sourced from the original CHARLS questionnaire, while other covariates were extracted from the CHARLS harmonized dataset.

Statistical analysis

Participants' basic characteristics were described using descriptive statistics. The normality of the distribution of continuous variables was assessed using the Anderson–Darling test. Continuous variables were summarized as mean and standard deviation (SD) if they followed a normal distribution, and as median and interquartile range (IQR) if they were not normally distributed. Categorical variables were presented as frequencies and percentages.

We assessed the potential nonlinear relationships between urbanization score and frailty using RCS models with four knots at the 5th, 35th, 65th, and 95th percentiles. Then, variance analysis was used to complete nonlinear tests. The urbanization score associated with the lowest risk of frailty was the score with the lowest hazard ratio (HR) on the spline curve. The covariates adjusted for in the model included age, gender, marital status, education levels, first job, youthful health condition, current work status, labor force status, household consumption, family support, participation in social activities, drinking status, smoking status, public health insurance coverage, four chronic diseases, dyslipidemia, liver disease, kidney disease, gastric or digestive disease, BMI, and $PM_{2.5}$.

We categorized urbanization indicators into ten levels using the Jenks Natural Breaks Classification, which enables grouping based on the inherent natural grouping of data. Cox proportional hazards models were employed to explore and quantify the relationship between urbanization level and frailty risk. In cases where there was evidence of non-linearity, Cox proportional hazards models were applied to both sides of the change point to verify the inflection point of the nonlinear relationship. Subgroup analysis was then conducted, stratified by age, gender, marital status, current work status, participation in social activities, drinking status, smoking status, public health insurance coverage, status of four chronic diseases, and obesity, to evaluate the heterogeneity among different populations. Moreover, according to the Criteria of Weight for Adults in China, obesity was defined as a $BMI \geq 28.0\ kg/m^2$ [40, 41].

We also conducted dimensionality reduction on the 19 urbanization indicator variables through standardized LASSO regression, selecting variables with non-zero coefficient features to explore the urbanization indicators contributing to the frailty incidence.

In this study, the nonparametric random forest imputation method, implemented using the missForest procedure in R, was applied to handle missing values in covariates. R software (version 4.3.3) was used to perform all statistical analyses and create all graphs; a two-sided $P < 0.05$ was considered statistically significant.

Sensitivity analysis

Eight sensitivity analyses were performed to check the robustness of the results. In sensitivity analysis 1, the adjustment for chronic conditions was omitted, and individuals with pre-existing chronic conditions at the initiation of the follow-up were entirely excluded. In sensitivity analysis 2, we investigated whether the association would change if the method of imputing missing covariate values were changed to the K-nearest neighbors imputation method. In sensitivity analysis 3, considering the possible reverse causality, we reanalyzed the association between urbanization level and frailty, excluding participants who experienced a frailty event within the first 2 years of follow-up. In sensitivity analyses 4 and 5, to account for the potential impact of changes in urbanization levels during the follow-up period, we performed a time-varying Cox proportional hazards regression using urbanization levels as time-dependent variables. Additionally, we conducted a Cox regression analysis using the average urbanization level from 2011 to 2018 as the exposure variable. In sensitivity analysis 6, to minimize the influence of participants who changed their residence on the results, we excluded individuals whose residence may have changed between cities during the follow-up surveys. In sensitivity analysis 7, to control for the effects of other air pollutants, namely particulate matter 10 (PM_{10}) and nitrogen dioxide (NO_2), on the outcome, we included PM_{10} and NO_2 as adjustment covariates. In sensitivity analysis 8, to account for the impact of missing variables on the study results, variables with a missing rate > 10%, as shown in Additional file 1: Table S4, including household consumption and BMI, were converted into binary variables (0 for non-missing; 1 for missing) and included as covariates for adjustment.

Results

Baseline characteristics of the study population

The primary analysis involved 10,758 participants, with a median age of 57 years (IQR, 51–64), and 50.86% were male. The baseline characteristics of the participants are summarized in Table 1. Among the overall population, 24.2% of participants had frailty. Compared with participants without frailty, those with frailty tended to be older, female, and unmarried. They were also more likely to have lower levels of education, poorer health at younger ages, and often started their careers in agriculture. Moreover, they were more likely to be unemployed and had lower household consumption. Additionally, they had less family support and lower participation in social activities. However, they were less likely to smoke and drink, slightly more likely to lack health insurance, more prone to dyslipidemia, kidney disease, and gastric or digestive disease, and tended to have an abnormal body mass index.

Figure 2 shows a map depicting the distribution of urbanization scores and the number of study participants in 101 cities in China. It can be observed that cities with high or relatively high urbanization scores are mainly distributed in the coastal areas. Meanwhile, the study subjects are more distributed in areas with low and relatively low urbanization levels. From Additional file 1: Table S5, the urbanization scores in 2011 were highest in Shenzhen, Guangzhou, Beijing, Shanghai, and Changsha, with scores of 0.689, 0.602, 0.488, 0.488, and 0.466, respectively, while the lowest scores were observed in Zhaotong, Lincang, Dingxi, Baoshan, and Bozhou, with scores of 0.072, 0.075, 0.082, 0.085, and 0.098, respectively.

Association between urbanization levels and frailty

To evaluate the nonlinear relationship, we utilized RCS to estimate the association between urbanization score and frailty. The RCS models revealed a U-shaped association. The risk of frailty decreased as the level of urbanization increased when the urbanization score was less than 0.3. However, the risk of frailty increased with higher urbanization levels (urbanization score ≥ 0.3) (P for non-linearity < 0.001) (Fig. 3). After adjusting for potential covariates, including age, sex, marital status, education levels, first job, youthful health condition, current work status, household consumption, family support, participation in social activities, smoking status, drinking status, public health insurance coverage, dyslipidemia, liver disease, kidney disease, gastric or digestive disease, BMI, and $PM_{2.5}$, the results showed that for urbanization score below 0.3, each decile increase in urbanization score corresponded to a 12.9% decrease in the risk of frailty (HR 0.871, 95% CI 0.843–0.900, $P < 0.05$) (Table 2). Conversely, for urbanization score of 0.3 or higher, each decile increase in urbanization level implied a 17.8% higher risk of frailty (HR 1.178, 95% CI 1.053–1.319, $P < 0.05$) (Table 2).

Subgroup analysis of urbanization level and the risk of frailty

In the subgroup analysis of individuals with urbanization scores < 0.3 (Fig. 4), the results remained consistent with the main analysis, indicating a negative correlation between urbanization level and frailty. Furthermore, we investigated the interactions between urbanization and current work status, as well as dyslipidemia, and their effects on frailty risk in individuals. Specifically, the correlation between urbanization and frailty risk was stronger in employed individuals compared to the unemployed (unemployed, HR: 0.932, 95% CI: 0.884–0.982; employed, HR: 0.849, 95% CI: 0.814–0.885, P interaction < 0.05). Moreover, the protective effect was more pronounced among individuals without dyslipidemia compared to those with dyslipidemia (without dyslipidemia, HR: 0.868, 95% CI: 0.838–0.898; with dyslipidemia, HR: 0.969, 95% CI: 0.876–1.071, P interaction < 0.05).

Figure 5 displays the subgroup analysis results for urbanization scores ≥ 0.3. Among these analyses, a significant association between urbanization level and frailty risk remained in subgroups defined by age ≥ 60 years, male gender, married status, non-obesity, current smoking status, non-drinking, employment status, participation in social activities, absence of dyslipidemia, absence of kidney disease, absence of digestive diseases, and presence of public health insurance ($P < 0.05$). Additionally, no interactions were observed in these subgroups.

Determine the dominant factors of urbanization that affect frailty

In the LASSO regression model, the regression coefficients were used to evaluate the relative importance of

Table 1 Baseline characteristics of participants with and without frailty from 2011 to 2018

Characteristics	Total (*N* = 10,758)	Non-frailty (*N* = 8155)	Frailty (*N* = 2603)
Population statistics			
Age, median [IQR], years	57.00 [51.00, 64.00]	56.00 [49.00, 62.00]	61.00 [55.00, 68.00]
Sex, *n* (%)			
Female	5286 (49.14)	3728 (45.71)	1558 (59.85)
Male	5472 (50.86)	4427 (54.29)	1045 (40.15)
Marital status, *n* (%)			
Non-married	1152 (10.71)	725 (8.89)	427 (16.40)
Married	9606 (89.29)	7430 (91.11)	2176 (83.60)
Early life			
Education level, *n* (%)			
Illiterate	2656 (24.69)	1674 (20.53)	982 (37.73)
Primary school education or below	4277 (39.76)	3175 (38.93)	1102 (42.34)
Education prior to bachelor's degree	3597 (33.44)	3096 (37.96)	501 (19.25)
Bachelor's degree or higher	228 (2.12)	210 (2.58)	18 (0.69)
First job, *n* (%)			
Government departments	219 (2.04)	178 (2.19)	41 (1.58)
Public institutions	485 (4.52)	414 (5.09)	71 (2.73)
Nonprofit organizations	27 (0.25)	24 (0.29)	3 (0.12)
Enterprises	1044 (9.72)	874 (10.74)	170 (6.55)
Sole proprietorship	257 (2.39)	212 (2.60)	45 (1.73)
Farm household	7393 (68.85)	5415 (66.52)	1978 (76.16)
Residential household	44 (0.41)	33 (0.41)	11 (0.42)
Others	373 (3.47)	287 (3.53)	86 (3.31)
Youthful health condition, *n* (%)			
Excellent	1112 (10.34)	893 (10.95)	219 (8.41)
Very good	3950 (36.72)	3009 (36.90)	941 (36.15)
Good	3022 (28.09)	2295 (28.14)	727 (27.93)
Common	1806 (16.79)	1327 (16.27)	479 (18.40)
Poor	692 (6.43)	490 (6.01)	202 (7.76)
Social economy			
Current work status, *n* (%)			
Unemployed	3385 (31.94)	2317 (28.84)	1068 (41.65)
Employed	7213 (68.06)	5717 (71.16)	1496 (58.35)
Household consumption (yuan, median [IQR])	17,160.00 [9120.00, 28,596.00]	18,038.00 [9742.50, 29,960.00]	13,952.00 [7740.00, 24,980.00]
Social psychology			
Family support, *n* (%)			
Living with children	6458 (60.13)	5051 (62.04)	1407 (54.14)
Meeting with children weekly	2200 (20.48)	1550 (19.04)	650 (25.01)
Meeting virtually with children weekly	1113 (10.36)	849 (10.43)	264 (10.16)
Having children without support	733 (6.82)	524 (6.44)	209 (8.04)
Having no children and no support	236 (2.20)	167 (2.05)	69 (2.65)
Participation in social activities, *n* (%)			
No	4999 (49.88)	3637 (48.18)	1362 (55.05)
Yes	5024 (50.12)	3912 (51.82)	1112 (44.95)
Behavioral factors			
Drinking status, *n* (%)			
Non-drinker	7793 (78.29)	5755 (76.72)	2038 (83.08)
Current drinker	2161 (21.71)	1746 (23.28)	415 (16.92)

Table 1 (continued)

Characteristics	Total (N = 10,758)	Non-frailty (N = 8155)	Frailty (N = 2603)
Smoking status, *n* (%)			
Non-smoker	7126 (68.68)	5241 (66.97)	1885 (73.92)
Current smoker	3250 (31.32)	2585 (33.03)	665 (26.08)
Public health insurance coverage, *n* (%)			
Not covered	807 (7.50)	602 (7.38)	205 (7.88)
Covered	9900 (92.02)	7515 (92.15)	2385 (91.63)
Chronic disease			
Dyslipidemia, *n* (%)			
No	9702 (90.18)	7416 (90.94)	2286 (87.82)
Yes	895 (8.32)	615 (7.54)	280 (10.76)
Liver disease, *n* (%)			
No	10,402 (97.10)	7904 (97.32)	2498 (96.41)
Yes	311 (2.90)	218 (2.68)	93 (3.59)
Kidney disease, *n* (%)			
No	10,257 (95.72)	7850 (96.63)	2407 (92.86)
Yes	459 (4.28)	274 (3.37)	185 (7.14)
Gastric or digestive diseases, *n* (%)			
No	8672 (80.80)	6732 (82.75)	1940 (74.67)
Yes	2061 (19.20)	1403 (17.25)	658 (25.33)
BMI, *n* (%), kg/m^2			
Underweight	567 (6.53)	366 (5.66)	201 (9.10)
Normal	4681 (53.93)	3588 (55.45)	1093 (49.50)
Overweight	2525 (29.09)	1908 (29.49)	617 (27.94)
Obesity	906 (10.44)	609 (9.41)	297 (13.45)
$PM_{2.5}$, median [IQR], microgram/cubic meter	51.75 [41.62, 64.18]	51.75 [41.62, 64.18]	52.20 [41.62, 64.16]

Abbreviation: *IQR* interquartile range, *BMI* body mass index, $PM_{2.5}$ particulate matter 2.5

the selected urbanization variables in predicting the outcome. Larger absolute values of the coefficients indicate a stronger association with the frailty and the direction of the relationship (positive or negative). The coefficient represented the correlation between the selected urbanization indicators and frailty. The tabulated data (Table 3) reveals that when the urbanization level falls below 0.3, the LASSO regression results showed that several urbanization assessment variables may impact on frailty risk. Specifically, the population density (coefficient = −0.039), total retail sales of consumer goods per capita (coefficient = −0.129), per capita disposable income of urban residents (coefficient = −0.071), number of beds per 10,000 people (coefficient = −0.011), the proportion of built-up land in the urban area (coefficient = −0.005), and green coverage rate of completed areas (coefficient = −0.043) were associated with a decrease in the risk of frailty. Other factors, such as urbanization rate, the proportion of the population in secondary industry, and various infrastructure indicators, were found to have zero coefficient. As shown in Table 4, when the urbanization level equals or exceeds 0.3, among all urbanization assessment variables, the investment in social fixed assets (coefficient = 0.020), number of college students per 10,000 people (coefficient = 0.080), and the proportion of built-up land in the urban area (coefficient = 0.060) were positively associated with the risk of frailty. Conversely, the green coverage rate of completed areas (coefficient = −0.052) and built-up urban land area per 10,000 people (coefficient = −0.110) was negatively associated with the risk of frailty. Other urbanization factors, such as urbanization rate, population density, and various economic and infrastructure indicators, did not significantly affect frailty risk.

Sensitivity analysis

Several sensitivity analyses were conducted to assess the robustness of our findings, as detailed in Additional file 1: Figs. S1–S7 and Additional file 1: Table S6. These analyses included (1) excluding participants with pre-existing chronic conditions at baseline, (2) applying the K-nearest neighbors imputation method to handle

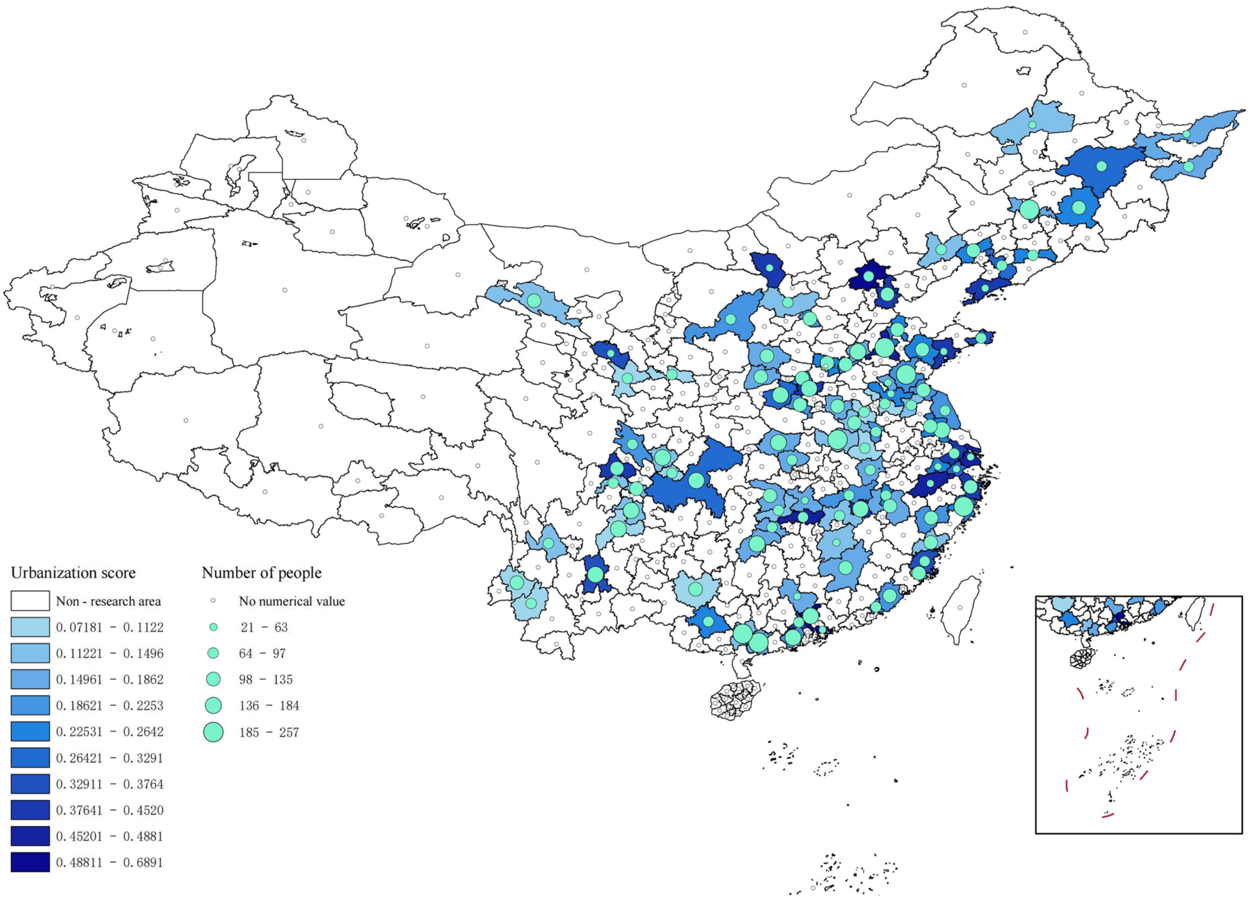

Fig. 2 Map of urbanization scores and population distribution in the study cities

missing covariate data, (3) excluding participants whose frailty events occurred within the first 2 years of follow-up, (4) treating urbanization levels across four periods (2011–2018) as time-varying variables to evaluate their association with frailty, (5) calculating the average urbanization level across the four survey waves from 2011 to 2018 as an exposure variable, (6) excluding participants who changed residence during the follow-up period, (7) including PM_{10} and NO_2 as covariates for adjustment in the analysis, and (8) variables with a missing rate > 10% were converted into binary variables (0 for non-missing; 1 for missing) and included in the adjustment model. The results from all sensitivity analyses were consistent with the main findings, reinforcing the stability and robustness of our conclusions.

Discussions

Overall, the findings from this prospective cohort study based on the CHARLS dataset emphasize a U-shaped nonlinear association between urbanization and frailty risk among middle-aged and older adults in China, with the lowest risk observed at a composite urbanization score of 0.3. Notably, when the urbanization score was < 0.3, the protective association was stronger among employed participants than unemployed ones and among those without dyslipidemia than those with it. Further, LASSO regression analysis revealed that the key urbanization indicators contributing to frailty protection were the per capita retail sales of consumer goods, followed by urban residents' per capita disposable income and green coverage in built-up areas. On the other hand, when the urbanization score was ≥ 0.3, the primary urbanization risk factor for frailty was the number of college students per 10,000 people, followed by the proportion of urban built-up areas.

To the best of our knowledge, this study represents the first population-based prospective cohort to examine the relationship between urbanization levels and frailty risk comprehensively. Previous studies investigating the association between urbanization and other health outcomes have reported mixed findings. Some studies suggest that urbanization exerts positive effects on health. For example, a 2019 cross-sectional study in China found that higher levels of urbanization were associated with

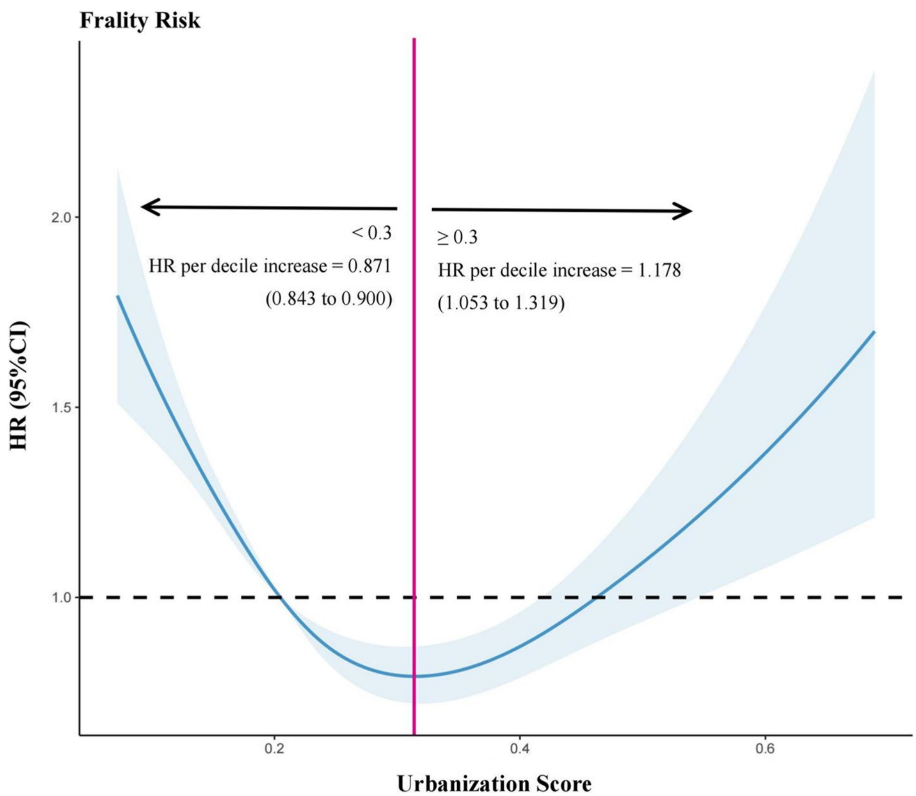

Fig. 3 Restricted cubic spline analyses with four knots for nonlinear association between urbanization score and the frailty outcome in total study population. Hazard ratios are indicated by solid lines and 95% CI by shaded areas. Reference point is lowest value for urbanization score. Analysis was adjusted for age, sex, marital status, education levels, first job, youthful health condition, current work status, household consumption, family support, participation in social activities, smoking status, drinking status, public health insurance coverage, dyslipidemia, liver disease, kidney disease, gastric or digestive disease, BMI, and $PM_{2.5}$. HR, hazard ratio; CI, confidence interval; BMI, body mass index; $PM_{2.5}$, particulate matter 2.5

improved self-reported health status and reduced depression levels [4]. Similarly, a 2022 cohort study conducted in the USA reported that urbanization was associated with decreased mortality from Alzheimer's disease [42]. On the other hand, some studies have suggested that higher levels of urbanization may contribute to adverse health outcomes. For instance, a 2012 spatial analysis of urbanization and health in China found that regions with the highest urbanization levels were more likely to experience higher incidences of chronic diseases [43]. Furthermore, a 2021 study involving the Chinese population reported that urbanization development was associated with an increased prevalence of chronic kidney disease [44]. Several factors may explain these inconsistencies in findings. First, variations in the overall levels of urbanization considered in different studies may result in gradient differences and divergent findings. Second, discrepancies in the methods used to assess urbanization could significantly contribute to these inconsistencies. Some studies have relied exclusively on single indicators, such as demographic or economic metrics, which may fail to capture the multifaceted nature of urbanization fully. In contrast, our study is the first to employ a composite urbanization assessment framework to comprehensively evaluate urbanization across 101 cities in China and investigate its potential association with frailty. Our findings demonstrate that urbanization growth has contrasting effects on frailty, with opposing influences observed

Table 2 Associations of urbanization score with frailty

Model	Urbanization score < 0.3		Urbanization score ≥ 0.3	
	HR (95% CI)	*P*_value	HR (95% CI)	*P*_value
Model 1	0.851 (0.825, 0.877)	< 0.05	1.161 (1.051, 1.282)	< 0.05
Model 2	0.840 (0.815, 0.867)	< 0.05	1.096 (0.994, 1.208)	0.067
Model 3	0.871 (0.843, 0.900)	< 0.05	1.178 (1.053, 1.319)	< 0.05

Model 1: crude model; model 2: adjusting sex, age, and BMI; model 3: model 2 + additional adjusting marital status, education levels, first job, youthful health condition, current work status, household consumption, family support, participation in social activities, smoking status, drinking status, public health insurance coverage, dyslipidemia, liver disease, kidney disease, gastric or digestive diseases, and $PM_{2.5}$

Abbreviation: *HR* hazard ratio, *CI* confidence interval, *BMI* body mass index, $PM_{2.5}$ particulate matter 2.5

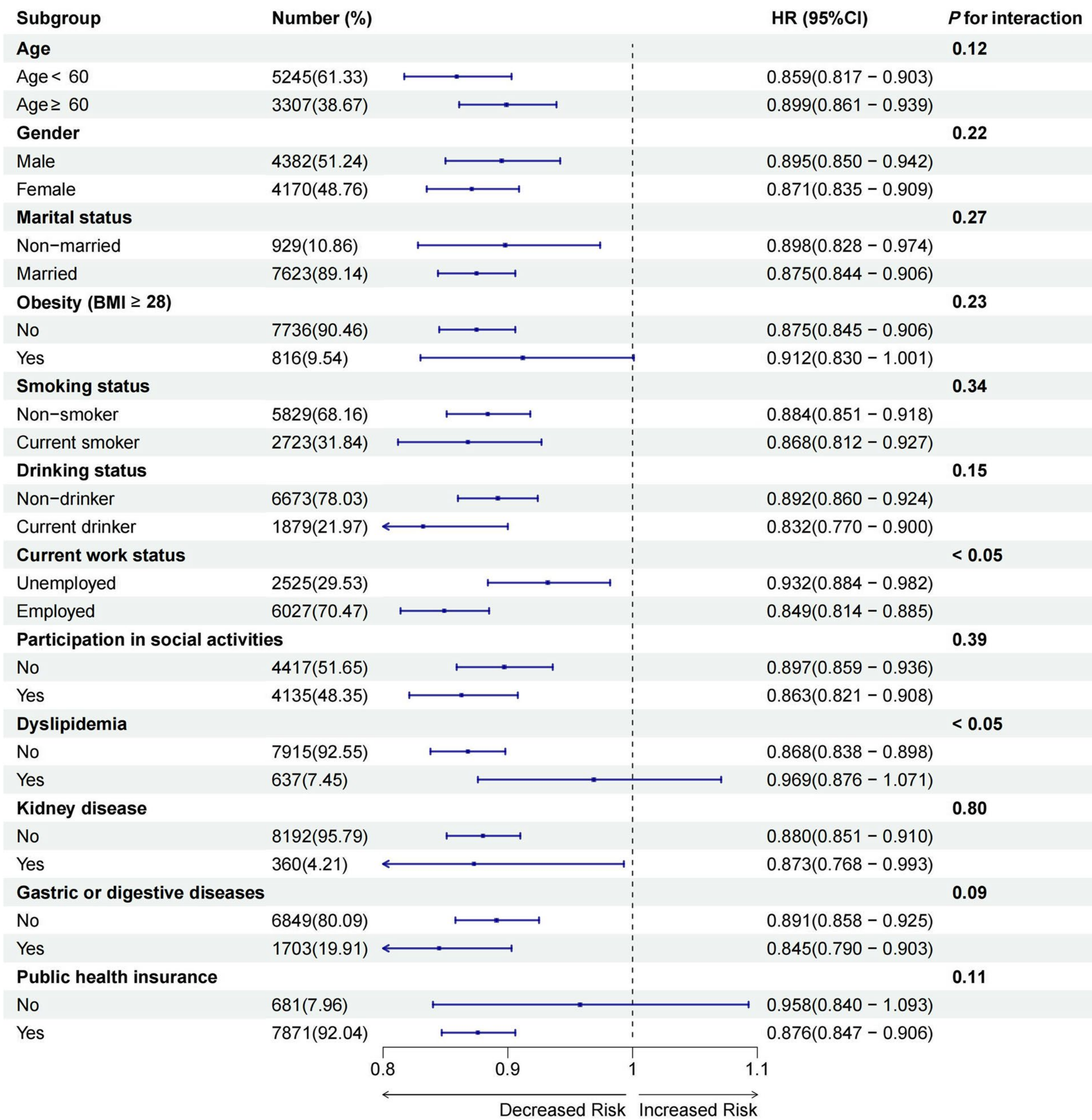

Fig. 4 Subgroup analysis to the left of the change point. Analysis was adjusted for age, sex, marital status, education levels, first job, youthful health condition, current work status, household consumption, family support, participation in social activities, smoking status, drinking status, public health insurance coverage, dyslipidemia, liver disease, kidney disease, gastric or digestive disease, BMI, and $PM_{2.5}$. However, corresponding subgroup analyses did not adjust for the factor being examined. HR, hazard ratio; CI, confidence interval; BMI, body mass index; $PM_{2.5}$, particulate matter 2.5

before and after the urbanization score reaches 0.3. This comprehensive approach mitigates the biases and limitations associated with single-indicator measurements, offering a more accurate reflection of urbanization's complexity and its nonlinear health effects.

In the phase where the urbanization score is < 0.3, the protective effect of urbanization on frailty is significantly stronger among participants who are currently employed compared to those who are not employed. Specifically, middle-aged and older adults who are employed benefit more from the urbanization process, suggesting that occupational participation may be a key factor in strengthening the protective effects in this population. This finding is consistent with previous research. Several studies have shown that continued employment in later life positively affects mental health [45, 46], helps

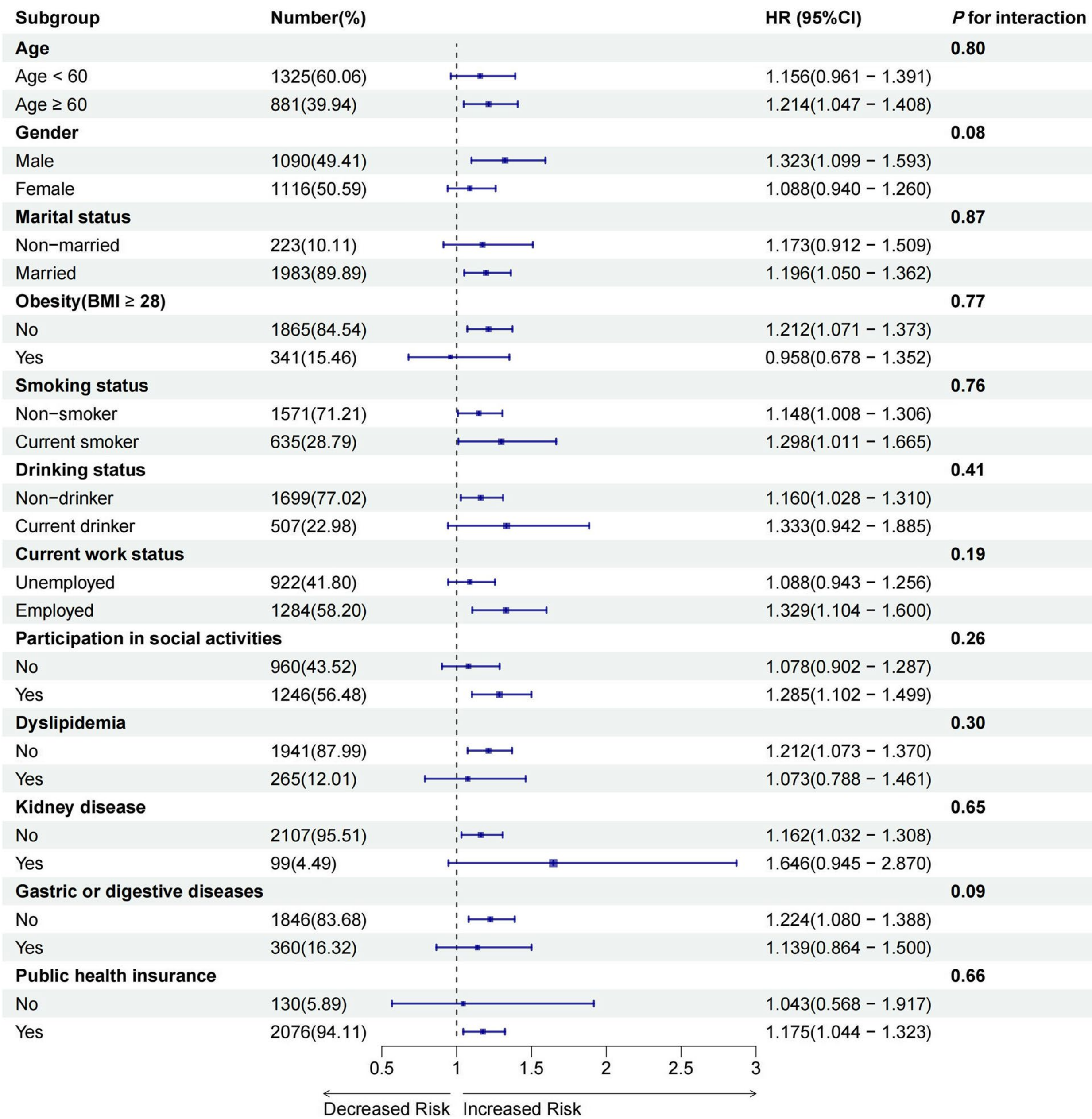

Fig. 5 Subgroup analysis to the right of the change point. Analysis was adjusted for age, sex, marital status, education levels, first job, youthful health condition, current work status, household consumption, family support, participation in social activities, smoking status, drinking status, public health insurance coverage, dyslipidemia, liver disease, kidney disease, gastric or digestive disease, BMI, and $PM_{2.5}$. However, corresponding subgroup analyses did not adjust for the factor being examined. HR, hazard ratio; CI, confidence interval; BMI, body mass index; $PM_{2.5}$, particulate matter 2.5

maintain physical and cognitive functions [47], and may further reduce the risk of frailty by enhancing social interaction and psychological resilience. Recent studies on the older people in China have also indicated that continued employment after retirement significantly reduces the risk of frailty [48]. From a potential mechanism perspective, improvements brought about by urbanization, such as increased income, healthcare resources, and infrastructure, may exert a stronger protective effect on frailty through enhanced occupational participation. Employed middle-aged and older adults are more likely to maintain higher levels of physical activity, mental engagement, and social connections, all of which have been shown to promote health [49, 50]. However, this protective effect may

Table 3 The relative importance of variables to the left of the change point

Variable	Coefficient[a]
Urbanization rate	–
Population density	−0.039
The proportion of population in secondary industry	–
The proportion of population in tertiary industry	–
Per capita GDP	–
The proportion of secondary industry to GDP	–
The proportion of tertiary industry to GDP	–
Investment in social fixed assets	–
GDP growth rate	–
Total retail sales of consumer goods per capita	−0.129
Per capita disposable income of urban residents	−0.071
Number of hospital beds per 10,000 people	−0.011
Number of doctors per 10,000 people	–
Number of public transport vehicles per 10,000 people	–
Number of college students per 10,000 people	–
The proportion of built-up land in the urban area	−0.005
Per capita urban road area	–
Green coverage rate of completed areas	−0.043
Built-up urban land area per 10,000 people	–

[a] The coefficients of less important or collinearity variables shrunk to zero

Abbreviation: *GDP* gross domestic product

Table 4 The relative importance of variables to the left of the change point

Variable	Coefficient[a]
Urbanization rate	–
Population density	–
The proportion of population in secondary industry	–
The proportion of population in tertiary industry	–
Per capita GDP	–
The proportion of secondary industry to GDP	–
The proportion of tertiary industry to GDP	–
Investment in social fixed assets	0.020
GDP growth rate	–
Total retail sales of consumer goods per capita	–
Per capita disposable income of urban residents	–
Number of beds per 10,000 people	–
Number of doctors per 10,000 people	–
Number of public transport vehicles per 10,000 people	–
Number of college students per 10,000 people	0.080
The proportion of built-up land in the urban area	0.060
Per capita urban road area	–
Green coverage rate of completed areas	−0.052
Built-up urban land area per 10,000 people	−0.110

[a] The coefficients of less important or collinearity variables shrunk to zero

Abbreviation: *GDP* gross domestic product

vary according to occupational type and work intensity, and further research is needed to confirm this heterogeneity. To further explore the impact of chronic diseases on the relationship between urbanization and frailty, this study performed a stratified analysis based on chronic diseases, including dyslipidemia. The results revealed a significant interaction in the subgroup analysis stratified by dyslipidemia status. However, within the dyslipidemia group, the protective effect of urbanization on frailty did not achieve statistical significance. This finding may be attributed to the poorer baseline health status of individuals with dyslipidemia, potentially diminishing the health benefits associated with urbanization. Previous studies have suggested that aging and related cardiovascular diseases may accelerate the loss of lean body mass, while fat mass tends to increase, making older individuals more susceptible to cachexia and frailty [51]. These cardiovascular risks may partially counteract the protective effects of urbanization. Future studies with larger sample sizes are needed to deeply explore the disease-specific moderating effects on the relationship between urbanization and frailty and further uncover the combined health impacts of chronic diseases and factors such as occupational participation in the urbanization process.

Recent studies have suggested that the prevalence of frailty in communities is associated with macroeconomic indicators, such as per capita GDP, PPP, and per capita healthcare expenditure [21]. Based on this, the present study further explores the impact of 19 urbanization-related indicators, which form a comprehensive urbanization assessment system, on frailty risk at different stages of urbanization through LASSO regression.

The results of this study indicate that, during the phase when the urbanization score is <0.3, per capita retail sales of consumer goods and per capita disposable income of urban residents are the most important protective factors against frailty. This finding is consistent with previous studies, which have shown that income and changes in income are generally positively correlated with better health and longer life expectancy [52–54]. Furthermore, the increase in green coverage in built-up areas improves residents' well-being and health by alleviating ecological stress and enhancing the living environment [55, 56]. Densely populated urban areas may further complement this effect by promoting social interaction, driving economic development, and improving infrastructure and healthcare services, all collectively reducing the risk of frailty [57, 58]. Additionally, the number of hospital beds per 10,000 people and the proportion of urban built-up land also play a protective role in frailty risk during the early stages of urbanization. The availability of hospital beds ensures the health of residents, while an increase in the proportion of built-up areas indirectly promotes residents' physical and mental health through enhanced socioeconomic development and improved living spaces [59–61]. These findings suggest that, in the early stages of urbanization, strategies such as increasing income levels, improving green coverage, and expanding healthcare resources may be key to reducing the risk of frailty.

When the level of urbanization reaches 0.3 or above, the study finds that an increasing number of university students may be one of the potential factors influencing the rising frailty risk among middle-aged and older adults at this stage. This phenomenon could be related to the growing competition for urban resources, such as housing, transportation, and healthcare [62]. However, the association between the expansion of higher education and the health of middle-aged and older adults remains underexplored. The findings of this study suggest that further research is needed to evaluate the potential impact of educational expansion and the imbalance in resource distribution on health. This study further highlights that the impact of the proportion of built-up urban land on frailty risk has undergone a significant shift, transitioning from a protective factor in the early stages of urbanization to a risk factor for frailty in more urbanized areas. In contrast, the built-up urban land area per 10,000 people and the green coverage rate of completed areas act as protective factors against frailty during this stage of urbanization. Unlike previous studies that primarily emphasized total urban green space coverage [63], this study focuses on the potential association between per capita urban built-up land area and frailty risk. This finding suggests that rational urban planning should place greater emphasis on optimizing residential space and increasing green coverage in urbanized areas to mitigate the adverse health impacts associated with the rapid expansion of urban land [64–66]. Furthermore, fixed asset investment during this stage has a slight risk effect on frailty. Previous studies have shown that fixed asset investment in China is heavily concentrated in the secondary industry, and this persistent over-investment, or investment lacking ecological consideration, has severely disrupted the urban-ecological balance, thereby increasing the risk of frailty [67, 68].

In summary, based on our research findings, during the early stages of urbanization, priority should be given to enhancing residents' income levels and increasing green space coverage, while policy interventions should focus on ensuring a balance between economic development and ecological sustainability. In the later stages of urbanization, efforts should shift toward optimizing land use planning, controlling excessive development, expanding living space, and promoting urban greening, which may be more effective in reducing the risk of frailty in middle-aged and older adults.

We believe our study has several strengths, including but not limited to the following aspects. First, we constructed a comprehensive urbanization assessment system incorporating 19 indicators across four dimensions: population, economy, society, and spatial development. This approach allowed us to systematically analyze the association between integrated urbanization and health status, as measured by the frailty index. This assessment method accurately and comprehensively reflects the urbanization levels of various cities, thereby enhancing the validity and reliability of our findings. Second, the study employed a prospective design and included 10,758 middle-aged and older adults aged 45 years and above from 101 cities in China, representing diverse socioeconomic backgrounds. The large sample size provided sufficient statistical power to perform all relevant analyses, enabling a more thorough examination of the data. Moreover, we applied rigorous statistical methods and conducted various sensitivity analyses to ensure the robustness and consistency of our results. Additionally, we adjusted for factors such as family support and $PM_{2.5}$ exposure, which have not been adequately considered in previous studies. Furthermore, the CHARLS database, one of the most representative and reliable longitudinal studies of older adults in China, and the China Statistical Yearbook, published by the National Bureau of Statistics of China, provided reliable and high-quality data sources.

However, it is important to acknowledge the limitations of our study. First, due to regional statistical differences between various versions of the Statistical Yearbook, it is impossible to completely eliminate information bias. Second, this study is based on the CHARLS database, a prospective cohort study focusing on the urbanization process in China and its impact on middle-aged and older adults. Therefore, caution should be exercised when applying our findings to populations in other countries. Third, despite our thorough assessment and inclusion of potential confounders, the influence of some unmeasured confounders cannot be ruled out. Fourth, while the composite urbanization and frailty assessment indicators used in this study are comprehensive, they may present challenges in data collection for practical applications. The many indicators required to assess urbanization and frailty could complicate data collection and reduce convenience, particularly in real-world settings. Simplifying these indicators or developing more practical alternatives could enhance their feasibility and applicability in large-scale studies or clinical practice. Fifth, considering the significant impact of the COVID-19 pandemic on the 2020 CHARLS data, we included only the survey data from 2011 to 2018, resulting in a relatively short follow-up period of 5.9 years in this study. This limitation restricts our ability to capture long-term trends and associations between urbanization and frailty fully. Future studies with longer follow-up periods would provide stronger evidence better to understand the sustained impact of urbanization on frailty. Finally, it is crucial to recognize that, as an observational study, our research cannot establish causal relationships.

Conclusion

There is a U-shaped non-linear association between urbanization and frailty risk among middle-aged and older adults in China, with the lowest frailty risk observed at a comprehensive urbanization score of approximately 0.3. Subgroup analyses indicate that, in the early stages of urbanization, employed middle-aged and older adults have a significantly lower frailty risk compared to the unemployed, emphasizing the role of employment in enhancing resilience among middle-aged and older adults. Furthermore, LASSO regression analysis identifies key factors influencing frailty risk across different stages of urbanization, highlighting the importance of improving income levels, green coverage, and healthcare resources during the early urbanization stage, as well as the need to optimize land use and social resource allocation in more urbanized areas. Our study not only provides new insights into the relationship between urbanization and health but also offers scientific evidence for formulating stage-specific urban development policies and intervention strategies. Future research should focus on the adverse impacts of educational expansion, land use, and ecological balance on health during urbanization while mitigating frailty risk through economic development, optimization of green spaces, and healthcare resource distribution. Additionally, studies with longer follow-up periods are needed further to explore the long-term dynamic effects of urbanization on health.

Abbreviations

CHARLS	China Health and Retirement Longitudinal Study
FI	Frailty index
RCS	Restricted cubic spline
LASSO	Least absolute shrinkage and selection operator
HR	Hazard ratio
CI	Confidence interval
BMI	Body mass index
$PM_{2.5}$	Particulate matter 2.5
PM_{10}	Particulate matter 10
NO_2	Nitrogen dioxide
CHAP	ChinaHighAirPollutants
SD	Standard deviation
IQR	Interquartile range
GDP	Gross domestic product

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12916-025-03961-y.

Additional file 1: Fig. S1. Sensitivity analysis on the association of urbanization level with frailty by excluding the individuals with chronic conditions at the initiation of the follow-up. Fig. S2. Sensitivity analysis on the association of urbanization level with frailty by the K-nearest neighbors imputation method to impute missing values. Fig. S3. Sensitivity analysis on the association of urbanization level with frailty by excluding participants whose frailty event occurred in the first 2 years of follow-up. Fig. S4. Sensitivity analysis of the association between urbanization level and frailty by using the average urbanization level from 2011 to 2018 as the exposure variable. Fig. S5. Sensitivity analysis of the association between urbanization and frailty excluding participants with residential changes during follow-up surveys. Fig. S6. Sensitivity analysis of the association between urbanization and frailty was conducted by adjusting for the covariates PM_{10} and NO_2. Fig. S7. Sensitivity analysis of urbanization and frailty, accounting for missing data in household consumption and BMI. Table S1. The urbanization evaluation index system and indicator weightings. Table S2. The 32 items used to construct the frailty index. Table S3. Covariate description table. Table S4. The percentages of participants with missing covariates involved in the analysis of this study. Table S5. The urbanization scores of the 101 cities. Table S6. The association between time-varying urbanization levels and frailty.

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Authors' contributions

XX, JQ: Data curation, Formal analysis, Methodology, Writing an original draft. XX, JQ, LS: Software, Supervision, Visualization. TS, FY: Validation, Writing - review & editing. All authors read and approved the final manuscript.

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Data availability

The data that support the findings of this study are available from the official websites of the statistical bureaus of various provinces and municipalities in China and the website of the China Health and Retirement Longitudinal Study (CHARLS) at http://charls.pku.edu.cn/.

Declarations

Ethics approval and consent to participate

CHARLS was ethically approved by the Institutional Review Board at Peking University (00001052–11014, 00001052–11015).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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