BMC Public Health

RESEARCH

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Social isolation in relation to the incidence and dynamic progression of frailty in the oldest old: a trajectory analysis of a nationwide cohort

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Abstract

Background There is still a lack of evidence examining the association of behavioral and social factors with frailty transitions and mortality. We investigated whether social isolation is associated with different progressions and outcomes of frailty among community-dwelling older adults.

Methods This community-based cohort study assessed the frailty index and objective social isolation of 31,168 participants (58.3% female; average age: 88.1 ± 11.1 years) from the Chinese Longitudinal Healthy Longevity Survey (CLHLS) from 1998 to 2018. Four Markov state-transition models were constructed to examine the associations between social isolation and the seven transitions of the frailty trajectory.

Results According to the Markov state-transition model, for every one-point increase in the social isolation score of non-frail participants, the risk of developing prefrailty increased by 4.2% [hazard ratio (HR) = 1.042, 95% confidence interval (CI): 1.007–1.079], whereas for prefrail participants, the risk of developing frailty and death increased by 3.9% (HR = 1.039, 95% CI: 1.007–1.073) and 16.1% (HR = 1.161, 95% CI: 1.099–1.226), respectively. For each increase in the social isolation score in the frail population, the risk of death increased by 2.9% (HR = 1.029, 95% CI: 1.004–1.054). Socially isolated persons had a greater cumulative transition probability to prefrailty and frailty. Socially isolated women were more likely to experience prefrailty and frailty than socially isolated men, whereas the latter were more likely to die from prefrailty and frailty than the former.

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Conclusions This study indicates that social isolation may contribute to an increased risk of both the incidence and progression of frailty, elevating deterioration risks in initially non-frail and prefrail populations, while primarily exacerbating mortality risks in those already experiencing prefrailty or frailty.

Keywords Social isolation, Frailty, Markov state-transition model, Frailty index, Cohort studies

Background

The oldest-old individuals (≥ 80 years) are the most vulnerable group to intrinsic or extrinsic stressors [1, 2]. Frailty, which is being widely associated with an increased risk of adverse health outcomes [3–6], is becoming a significant global public health challenge as the global older adult population grows rapidly. However, frailty is not a steady state but rather a dynamic process where improvement is possible, particularly in its early stages [7–12]. Although frailty appears to be reversible, worsening frailty is a common frailty transition, while complete remission is a rare event in the absence of an intervention [13, 14]. Identifying and targeting the prognostic factors that might accelerate or mitigate the progression from non-frailty, prefrailty, frailty, and death could aid specific clinical and personal decision-making regarding the timing and types of interventions to ensure effectiveness in managing frail older adults.

Numerous factors, including biological, psychological [15, 16], comorbidity, lifestyle, economic, and social factors [17], have been reported to be significantly associated with frailty [18–20]. Accordingly, various long-term modifiable risk factors for frailty, such as overweight/obesity [21, 22], physical inactivity [23, 24], cardiovascular risk [25, 26], alcohol use [27], and environmental influences [28, 29] have been identified. Social isolation, defined as the objective deficiency in social contact and interpersonal interactions, has been robustly linked to increased risks of morbidity and mortality [30]. While the protective effects of social relationships on physical and mental health are well-established [31], the role of social isolation in frailty trajectories and transitions between different stages of frailty remains unclear. Catharine Gale et al. reported that social isolation and loneliness are not associated with a change in the frailty index over a mean period of six years [32]. In contrast, Davies et al. highlighted an association between social isolation and frailty in a cohort of more than 9,000 participants [33]. Several existing longitudinal studies [19, 33–35] have examined frailty in primarily Western older adults via the FI [36, 37]. Nonetheless, at present, the evidence concerning the dynamic relationship between social isolation and frailty remains scarce. Accurate information regarding the trajectory from robust to frail to death (the prognosis) is fundamental for appropriate risk stratification [38] and service planning in vulnerable older populations. In addition, previous longitudinal studies [19, 34, 35] have examined frailty transitions primarily in Western older adults; therefore, comparatively little is known about frailty transitions in the older Chinese population. There is also a paucity of literature on frailty progression defined by a cumulative deficit model among community-dwelling older people [14]. Taken together, the association between frailty and social isolation is not fully understood in older adults, especially older adults in China.

Using a nationwide survey over a 20-year follow-up period with the largest dataset of oldest-old cohorts in the world, this study bridges the understanding between social isolation and frailty [1] and defines the relationships among social isolation, frailty progression, and death in advanced age so that relevant assessments and interventions can be targeted appropriately. We hypothesized that different early frailty transition patterns would be associated with social isolation.

Methods

Study design and participants

This longitudinal study used data from the Chinese Longitudinal Healthy Longevity Survey (CLHLS) [39], a large population-based cohort study conducted from 1998 to 2018 by Peking University using face-to-face interviews and self-completed questionnaires [40]. Data from the 1998–2018, 2000–2018, 2002–2018, 2005–2018, and 2008–2018 waves were used. (Fig. S1). We excluded participants who were < 65 or > 106 years old ($n = 770$), had missing values at baseline for any of the seven social isolation items ($n = 1999$), had < 80% indicators at baseline to calculate the frailty index ($n = 2104$), and were lost to follow-up in the subsequent follow-up survey ($n = 7350$). Overall, 31,168 participants who were followed up for seven waves were included in the analysis (Fig. S1). This study was approved by the Biomedical Ethics Committee of Peking University (IRB00001052–13074). All participants provided written informed consent.

Multidimensional frailty index

The frailty index were constructed following a standard procedure [41]. Multidimensional frailty was measured at baseline and follow-up on the basis of the Rockwood frailty index (FI) (deficit accumulation index), which has been validated in the CLHLS [42–45]. Our index was composed of 38 deficits, including self-rated health status, interviewer-rated health conditions, comorbidities, cognitive functioning based on Mini-mental state examination, basic activities of daily living measured by the

Barthel Activities of Daily Living Test [46], body function, psychological status, sensory function, heart rhythm, and oral health (Table S1). All variables were scored from 0 (absence of each deficit) to 1 (presence of each deficit), while 0.5 indicated an intermediate status. Similarly, variables that were scored on four- or five-point Likert scales were assigned corresponding ordinal values (0, 0.33, 0.67, and 1 on a four-point Likert scale and 0, 0.25, 0.5, 0.75, and 1 on a five-point Likert scale), with larger values indicating more severe impairment (Table S1) [42]. Subsequently, frailty was subsequently categorized using defined cut-off points to indicate individuals who were non-frail (≤ 0.08), prefrail (> 0.08 to < 0.25), or frail (≥ 0.25) [47].

Social isolation score

Social isolation was assessed at baseline according to previously published methods [48, 49], and included four domains: social engagement, living situation, social network, and social support (Table S2; Method S1). The four domains were incorporated into the model as unified social isolation scores due to their weak correlations, which were evaluated using Spearman's correlation coefficients (Fig. S2). The seven items were summed arithmetically by assigning one point for each item to provide a social isolation score ranging from 0 to 7, with higher scores indicating greater isolation. Using the overall mean social isolation score (mean = 2.76) as a reference, this study defined participants with a social isolation score > 3 as socially isolated.

Mortality

Mortality was measured on the basis of survival status and duration of exposure to death. Survival status was measured on the basis of whether a respondent interviewed in the baseline waves passed away or survived in subsequent waves. The exposure duration for a survivor was measured as the number of months between the interview date at baseline and subsequent waves. For those who passed before a certain wave, the exposure time was measured as the time interval between the date of death and the interview date in the previous wave. The date of death was collected from officially issued death certificates whenever available (> 80% of cases); otherwise the next-of-kin and local residential committees were consulted [50].

Covariates

In the analysis, important covariates with established associations to both frailty and social isolation were considered (Table S3) [51–53], including age, sex, residential area, education, household income, childhood socioeconomic status, intake of vegetables and fruits, smoking, drinking, and self-reported regular exercise at baseline. Comorbidities were not included as covariates because the entire set of components was included in the construction of the FI.

Statistical analysis

This study mainly used SPSS (version 26.0) to establish a database, and statistical analysis was conducted using R 4.4.2. The baseline characteristics of the analytical sample were summarized across three frailty states (i.e., non-frailty, prefrailty, and frailty) as percentages for categorical variables, and means and standard deviations for continuous variables. Missing values for the covariates were addressed through multiple imputation.

Seven transition phases were considered based on the natural history of frailty and possible reversal (Fig. 1A). Since frailty is a continuous process, we limited the direct conversion between non-frailty and frailty without prefrailty. This study revealed 48 direct transitions from frailty to non-frailty and 312 deteriorations from non-frailty to frailty (Table S4), which contradicted the frailty transition model we constructed. However, since the cohort was followed up every 3–4 years, prefrailty could occur in the middle of the observation period; thus, 48 transitions to both transitions (from prefrailty to non-frailty or from frailty to prefrailty), and 312 transitions to the two transitions (from non-frailty to prefrailty or from prefrailty to frailty) were incorporated into the analysis. Then, multinomial logit analysis was used to examine the association between social isolation and frailty at baseline.

Markov state-transition models were constructed to examine the associations between social isolation and the seven transitions of the frailty trajectory. Model 1 was unadjusted. Model 2 was adjusted for age at baseline and sex; Model 3 included the same adjustments as Model 2 plus education, residence, and household income; and Model 4 included the same adjustments as Model 3 plus childhood socioeconomic status, regular physical exercise, smoking, drinking, and vegetable and fruit intake. Furthermore, because only a 10-year follow-up period was used for the population enrolled in 2008–2018 (Fig. 1B), cumulative transition probabilities from prior to later states during the 10-year follow-up were predicted for participants with and without social isolation. Differences in cumulative transition probabilities between the sexes were further examined.

Sensitivity analysis

To assess the robustness of the results, several sensitivity analyses were conducted: (1) excluding participants without complete covariate data, the general characteristics of the included and excluded populations are shown in Table S5; (2) redefining the criteria for judging frailty as no frailty (FI ≤ 0.10), prefrailty (FI > 0.10 and < 0.21),

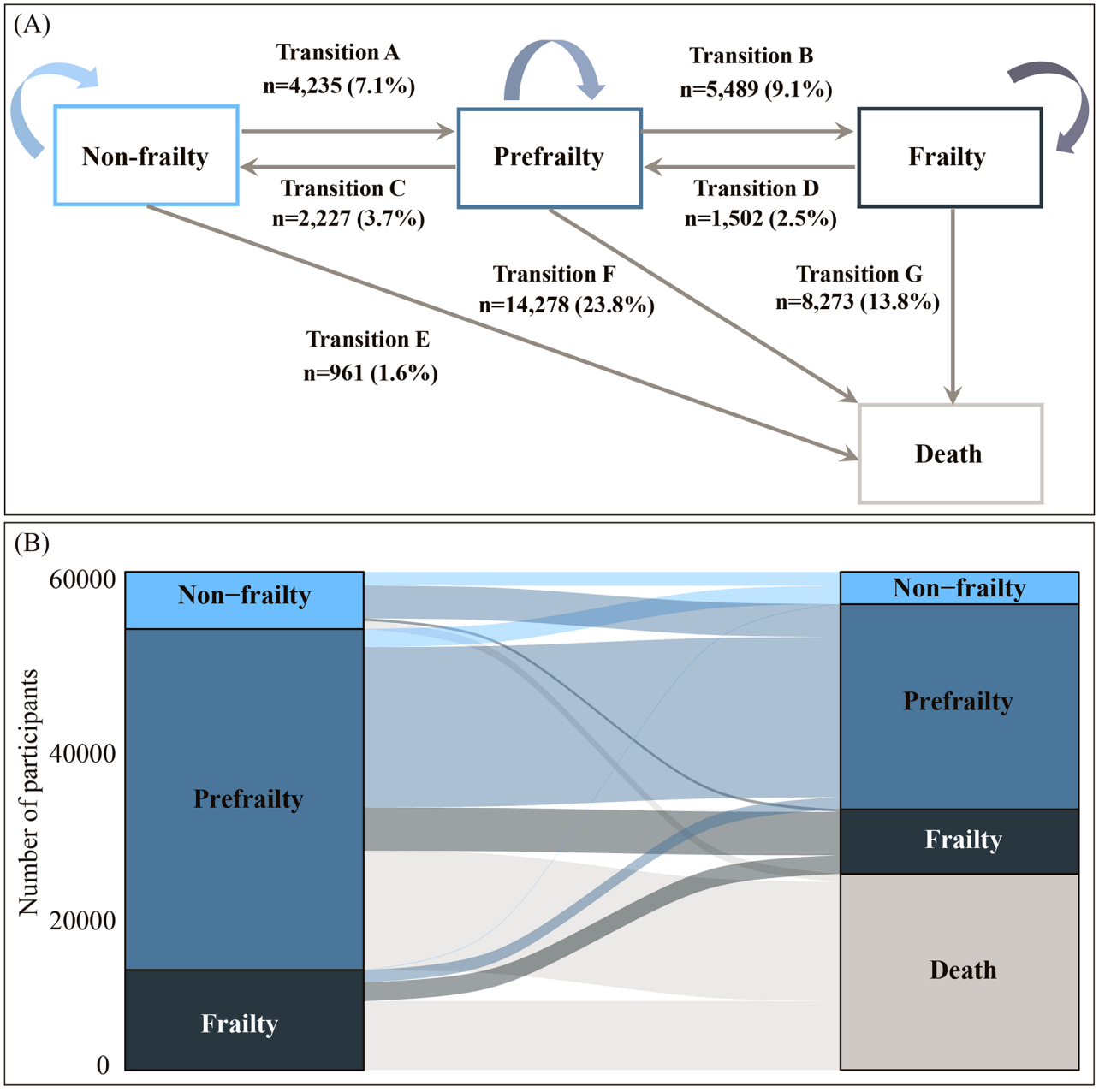

Fig. 1 State transition model and alluvial diagram. **A** shows the Markov model, with transitions from non-frailty to prefrailty, frailty, and all-cause death. Specific states are reported in boxes, and the transition-specific number of events and percentages (within brackets) are reported on the arrows. **B** shows the frailty state transitions depicted through the alluvial diagram

and frailty (FI ≥ 0.21) [54]; (3) incorporating education as a continuous variable into the model to counter partial information loss; and (4) investigating the correlation between baseline social isolation status and frailty progression using mixed-effect Poisson regression models.

Results

Descriptive results

A total of 31,168 participants were included in the study, including 4,831 from 1998, 6,224 from 2000, 8,031 from 2002, and 7,067 from 2005, with an average age of 88.1 (SD, 11.1) years at baseline. The average follow-up duration was 4.57 years (SD, 3.92) (last visit -baseline) [142,437.76 person years (PYs)]. At baseline, 5, 138 individuals [aged 89.9 (9.8) years] had social isolation, and 26, 030 had no social isolation [87.7 (11.3) years]. (Table 1). In subsequent years, 4,235 persons transitioned from non-frailty to prefrailty, 5,489 from prefrailty to frailty, 2,227 from prefrailty to non-frailty, 1,502 from frailty to prefrailty, 961 from non-frailty to death, 14,278 from

Table 1 Characteristics of 31,168 participants by social isolation

	Social isolation No. (%) (*n* = 5138)	Non-social isolation, No. (%) (*n* = 26030)	Overall, No. (%) (*n* = 31168)	*P*-value
Age, mean (SD), years	89.9 (9.8)	87.7 (11.3)	88.1 (11.1)	< 0.001
Sex				< 0.001
Male	1805 (35.1)	11,205 (43.0)	13,010 (41.7)	
Female	3333 (64.9)	14,825 (57.0)	18,158 (58.3)	
Residence				< 0.001
Rural	3269 (63.6)	15,598 (59.9)	18,867 (60.5)	
Urban	1869 (36.4)	10,432 (40.1)	12,301 (39.5)	
Education				< 0.001
Illiterate	3818 (74.3)	16,577 (63.7)	20,395 (65.4)	
Literate	1320 (25.7)	9453 (36.3)	10,773 (34.6)	
Missing	16	70	86	
Household income				< 0.001
Stable	506 (9.8)	4435 (17.0)	4941 (15.9)	
Unstable	4632 (90.2)	21,595 (83.0)	26,227 (84.1)	
Missing	0	1	1	
Childhood socioeconomic status				< 0.001
Poor	3613 (70.3)	17,465 (67.1)	21,078 (67.6)	
Great	1525 (29.7)	8565 (32.9)	10,090 (32.4)	
Missing	157	662	819	
Intake of vegetables				< 0.001
Yes	2845 (55.4)	16,307 (62.6)	19,152 (61.4)	
No	2293 (44.6)	9723 (37.4)	12,016 (38.6)	
Missing	0	13	13	
Intake of fruits				< 0.001
Yes	453 (8.8)	3516 (13.5)	3969 (12.7)	
No	4685 (91.2)	22,514 (86.5)	27,199 (87.3)	
Missing	0	10	10	
Smoking				< 0.001
Yes	1416 (27.6)	8790 (33.8)	10,206 (32.7)	
No	3722 (72.4)	17,240 (66.2)	20,962 (67.3)	
Missing	1	17	18	
Drinking				< 0.001
Yes	1421 (27.7)	8307 (31.9)	9728 (31.2)	
No	3717 (72.3)	17,723 (68.1)	21,440 (68.8)	
Missing	3	17	20	
Regular physical exercise				< 0.001
Yes	1172 (22.8)	7476 (28.7)	8648 (27.7)	
No	5138 (77.2)	18,554 (71.3)	22,520 (72.3)	
Missing	1	18	19	
Frailty index, mean (SD)	0.182 (0.102)	0.178 (0.104)	0.179 (0.104)	< 0.001
Frailty status				< 0.001
Non-frailty	524 (10.2)	3210 (12.3)	3734 (12.0)	
Prefrailty	3619 (70.4)	17,720 (68.1)	21,339 (68.5)	
Frailty	995 (19.4)	5100 (19.6)	6095 (19.6)	

prefrailty to death, and 8,273 from frailty to death (Fig. 1; Table S4). Figure 2 shows the frailty transitions among the population classified by social isolation. Table S6 presents the baseline characteristics of the participants based on frailty status. We also described the time-dependent distribution of social isolation among the 31,168 participants (Fig. S3). The prevalence of social isolation between 1998 and 2018 ranged from 11.9 to 16.8%, respectively. The participants with higher social isolation scores at baseline had greater risks of prefrailty (Relative risk ratio [RRR] = 1.137, 95% CI: 1.091–1.184) and frailty (RRR = 1.265, 95% CI: 1.199–1.335). (Table S7)

Associations between the social isolation score and progressions of frailty status

The associations between social isolation and the risk of frailty progression are presented in Table 2. A series of covariates, including age, sex, education level, place of residence, household income, childhood socioeconomic status, exercise, smoking, drinking, and vegetable and fruit intake, were included in the analysis. After adjusting for these potential covariates, for every one-point increase in the social isolation score in the non-frailty population, the risk of developing prefrailty increased by 4.2% (HR = 1.042, 95% CI: 1.007–1.079), whereas for every one-point increase in social isolation in the prefrailty population, the risk of developing frailty and death increased by 3.9% (HR = 1.039, 95% CI: 1.007–1.073) and 16.1% (HR = 1.161, 95% CI: 1.099–1.226), respectively. For every one-point increase in social isolation in the frail population, the risk of death increased by 2.9% (HR = 1.029, 95% CI: 1.004–1.054). However, no statistically significant association was observed between social isolation and improvement in frailty status.

Cumulative transition probability of frailty status

Figure 3 shows the cumulative transition probabilities of different progressions for the participants during the first 10 years. Figure 3A shows the probabilities for all participants of transitioning from non-frailty to prefrailty. The probability for the socially isolated participants was greater than that (0.1-1.1%) for the non-socially isolated participants until the 8.86-year follow-up. The probabilities of transitioning from prefrailty to frailty in socially isolated individuals were greater than those (0.3-1.5%) in non-socially isolated individuals until the 4.62-year follow-up (Fig. 3B). Throughout the follow-up period, the cumulative transition probabilities of transitioning from prefrailty to death (0.9-5.9%) (Fig. 3C) and transitioning from frailty to death (0.8-3.4%) (Fig. 3D) among socially isolated individuals were consistently greater than those in non-isolated individuals.

Compared with men with social isolation, women with social isolation were more likely to experience prefrailty

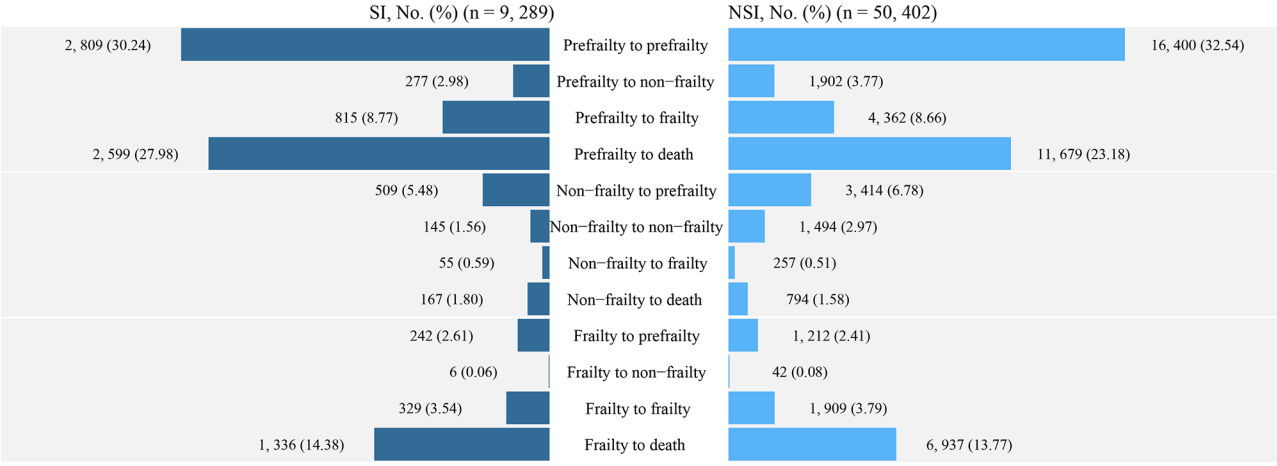

Fig. 2 Transition frequencies of different states in participants by social isolation

Table 2 Associations between social isolation and risk of seven progressions of frailty using the Markov state-transition model

Progressions of frailty	Model 1		Model 2		Model 3		Model 4	
	HR	95% CI	HR	95% CI	HR	95% CI	HR	95% CI
Non-frailty to prefrailty	**1.108**	**(1.072 ~ 1.145)**	**1.075**	**(1.041 ~ 1.111)**	**1.047**	**(1.012 ~ 1.083)**	**1.042**	**(1.007 ~ 1.079)**
Non-frailty to death	**1.265**	**(1.003 ~ 1.595)**	1.123	(0.979 ~ 1.289)	1.142	(0.992 ~ 1.316)	1.125	(0.979 ~ 1.294)
Prefrailty to non-frailty	**0.780**	**(0.739 ~ 0.823)**	0.965	(0.918 ~ 1.014)	0.961	(0.913 ~ 1.011)	0.960	(0.912 ~ 1.010)
Prefrailty to frailty	**1.205**	**(1.171 ~ 1.240)**	**1.042**	**(1.011 ~ 1.075)**	**1.043**	**(1.010 ~ 1.076)**	**1.039**	**(1.007 ~ 1.073)**
Prefrailty to death	**1.265**	**(1.231 ~ 1.301)**	**1.173**	**(1.114 ~ 1.235)**	**1.146**	**(1.086 ~ 1.210)**	**1.161**	**(1.099 ~ 1.226)**
Frailty to prefrailty	**0.877**	**(0.806 ~ 0.954)**	1.013	(0.952 ~ 1.078)	0.986	(0.926 ~ 1.050)	0.991	(0.930 ~ 1.056)
Frailty to death	**1.110**	**(1.083 ~ 1.138)**	**1.043**	**(1.019 ~ 1.068)**	**1.030**	**(1.006 ~ 1.056)**	**1.029**	**(1.004 ~ 1.054)**

Note: Model 1: Basic model was non-adjusted. Model 2: Adjusted for age and sex at baseline. Model 3: Adjusted for age, sex, education, household income and residence at baseline. Model 4: Adjusted for age, sex, education, household income, residence, childhood socioeconomic status, intake of vegetables and fruits, smoking, drinking and regular physical exercise at baseline. Significant results are marked in bold

Abbreviations: HR, hazard ratios; 95% CI, 95% confidence interval

(1.2-5.3%) (Fig. 3E) and frailty (0.2-2.2%) (Fig. 3F). However, men in social isolation were more likely to die from prefrailty (1.4-8.0%) (Fig. 3G) and frailty (3.3-8.6%) (Fig. 3H) than women in social isolation. (Table S8)

Sensitivity analyses

The results of the sensitivity analyses are presented in the Supplementary Materials. First, after excluding participants with missing values ($n = 953$), the correlation between social isolation and the four transitions remained significant (Model 1 in Table S9). Second, after using another cut-off points to define the different frailty categories, the results remained largely consistent with those of the main models (Model 2 in Table S9). When education level was subsequently considered as a continuous variable in the Markov model, for every one-point increase in social isolation in the prefrail population, the risk of developing frailty and death increased by 5.1% (HR = 1.051, 95% CI: 1.015–1.088) and 12.5% (HR = 1.125, 95% CI: 1.082–1.169), respectively. For every one-point increase in social isolation in the frail population, the risk of death increased by 3.5% (HR = 1.035, 95% CI: 1.006–1.065) (Model 3 in Table S9). Finally, we modeled the associations between social isolation and frailty states over time using mixed-effect Poisson regression models (Table S10) and reported that individuals with social isolation had elevated risks of transitioning from non-frailty to prefrailty (Estimate = 1.016, 95%CI: 1.006–1.027, $P = 0.002$) and frailty (Estimate = 1.089, 95%CI: 1.066–1.112, $P < 0.001$), as well as from prefrailty to frailty (Estimate = 1.051, 95%CI: 1.030–1.073, $P < 0.001$).

Discussion

To the best of our knowledge, this is the first study to use a large sample size and a broad timeframe of 20 years to analyze the associations between social isolation and the incidence and dynamic progression of frailty, as well as the differences in the effects of social isolation on the cumulative transfer probability among different sexes. Social isolation was independently associated with frailty at baseline and at different transition stages from non-frailty to prefrailty, to frailty, and then to death. Participants exposed to social isolation have an increased risk of adverse frailty outcomes. Further sensitivity analyses indicated that even if individuals with social isolation had lower FI at baseline, FI growth rates were faster than

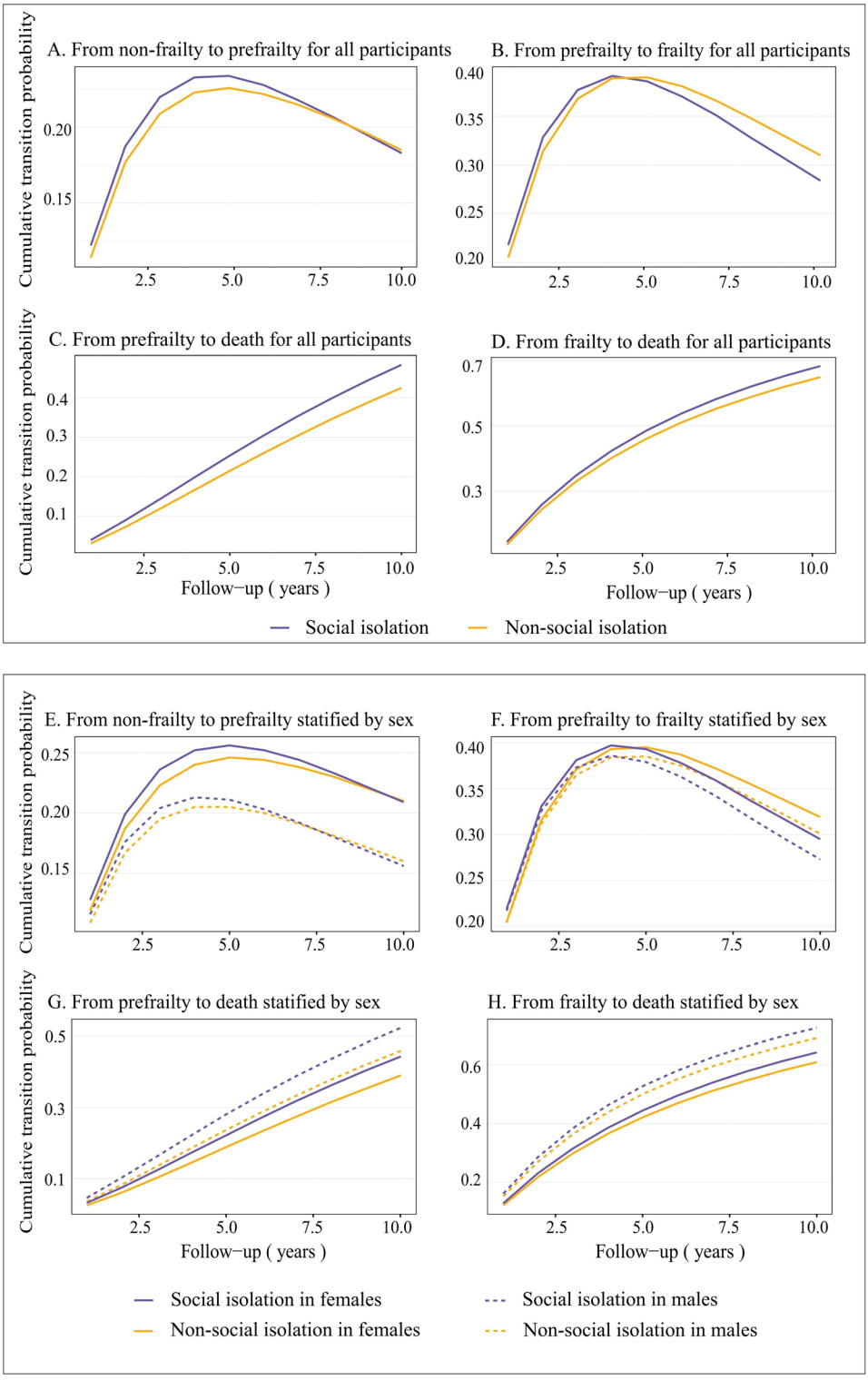

Fig. 3 Cumulative transition probabilities of frailty for participants exposed to the social isolation. Owing to the high number of deaths in the second 10 years of follow-up, this graph shows the cumulative transfer probabilities of frailty states exposed to social isolation (purple) or not (yellow) during the first 10 years, and the differences in cumulative transfer probabilities in females (continuous) and males (dotted). **A** (for all participants) and 3E (stratified by sex) show the transitions from non-frailty to prefrailty, whereas **B** (for all participants) and 3 F (stratified by sex) show the transitions from prefrailty to frailty; **C** (for all participants) and 3G (stratified by sex) show the transitions from prefrailty to death; and **D** (for all participants) and 3 H (stratified by sex) show the transitions from frailty to death. These models were adjusted for age, sex, education, household income, residence, childhood socioeconomic status, intake of vegetables and fruits, smoking, drinking, and regular physical exercise

those of individuals without social isolation during the follow-up years. Taken together, our results suggest that social isolation, quantified by living situation, social networks, social activities, and social support, can adversely affect frailty transitions.

Notably, starting from the fourth year of follow-up, the number of deaths or losses to follow-up significantly increased; people with higher social isolation scores had lower cumulative transition probabilities than those with non-social isolation because many participants who had higher levels of isolation passed away. In addition, we found that older women were more likely to experience a deterioration of frailty, whereas older men were more likely to die when they had the same status of social isolation. This finding offers the unique insight that although women seem to be more vulnerable in the face of social isolation, men face particularly severe consequences in terms of mortality risk. However, the underlying mechanism remains unclear. A previous study revealed that an inflammatory response is an important pathological mechanism of frailty syndrome [55]. This finding is significant because another study revealed that social isolation is related to the inflammatory response in males and females, whereas acute stressors have a sexually dimorphic effect, enhancing the inflammatory response in females and delaying it in males [56]. Frailty is more prevalent in women (55% vs. 45%) [57], yet men deteriorate faster [58] likely due to hormonal differences—estrogen loss accelerates frailty in women, while testosterone decline exacerbates muscle loss in men [59]. Male frailty is linked to reduced physical activity and cardiovascular risk, whereas female frailty is associated with inflammation and depression [60]. This suggests that the pathophysiological mechanisms are different, Neuroimaging reveals early white matter decline in men and limbic dysfunction in women. Behaviorally, Men benefit more from high-intensity exercise, while women respond better to low-intensity activities [60]. However, men experience earlier physical activity decline [58]. Socially, men's help lower-seeking behavior increases frailty risk [61], while women's caregiving roles often compromise their health [62]. Women living alone face a 2.3-fold higher frailty risk than men, reflecting gendered disparities in resource access [63].

Our results are consistent with previous studies reporting that social isolation and frailty are independent factors of mortality [18, 64, 65], and with more theoretical papers or reviews discussing the role that social factors play in predicting the risk of frailty in older adults [66]. In general, prospective longitudinal research with a long follow-up period to assess the effects of social isolation on frailty transition is scarce. Our study identified the relationship between physical isolation and frailty transitions. Compared with similar studies based on the same cohort, this study observed more waves and focused on evaluating the role of social isolation in the seven transitions between the four states. Liu et al. observed only one wave, some transitions in shorter time might not be captured in this study using a 3-year time period [67]. The initiators of this cohort study only observed only the all-cause mortality rate, prevalence of frailty, and disability in older people aged 80 years and above in two 10-year birth cohorts [1].

Different measures of social isolation and frailty can create differences in the observed associations. Cross-study comparisons are limited by inconsistent measurement approaches for both social isolation and frailty. For example, our analysis used a multi-item scoring system adapted to the CLHLS dataset, while other studies may define social isolation using simpler criteria (e.g., monthly in-person contact frequency). Similarly, we assessed frailty through a multidimensional index (FI) covering physical, psychological, and social domains, contrasting with studies relying solely on physical metrics (e.g., gait speed, grip strength) [2]. FI tends to identify a higher prevalence of frailty and capture graded changes over time [14], but these methodological differences create inherent comparability challenges. Additionally, variations in cohort age distributions and measurement protocols further complicate direct comparisons [14]. Interpretation of our findings should account for these measurement-specific contexts.

This study has several major strengths. First, it examines a large population-based cohort across multiple waves and contains detailed information on social isolation (95.4% completion rate), frailty (95.2% completion rate), socioeconomic, lifestyle, and health profile data with the CLHLS. This enabled us to construct a multistate model of frailty development and control for potential confounding factors. Second, unlike traditional Cox regression models, we used the Markov multistate model to distinguish the effects of social isolation on the seven transition phases. Thus, we were able to detect the sensitive stages of frailty development and how its progression could be affected by social isolation. The probability of transition between states, which helps us understand the interrelationship between social isolation and frailty as well as the possible causal relationships between them. Finally, a series of sensitivity analyses confirmed the robustness of the results.

There are also some limitations to this study, such as the following: (1) Some information regarding the evaluations was based on self-reports, which could lead to measurement errors. (2) Some participants were excluded because of missing data or loss to follow-up, which may have led to selection bias. (3) The proportion of socially isolated individuals may have been underestimated because individuals with social isolation or poor health

conditions were unlikely to participate in the study. (4) Temporal variations in social isolation during follow-up were not accounted for, but we examined the associations between baseline social isolation and subsequent frailty development and mortality. Most importantly, comorbidity and disabilities are also components of FI. To resolve residual confusion in future research, more detailed health assessments, including comprehensive medical history and diagnostic evaluations, are needed. Future studies should investigate the time-varying nature of social isolation and its dynamic relationships with both incident frailty progression and mortality outcomes.

Conclusion

Social isolation is longitudinally associated with frailty and is a predictor of frailty risk. These findings contribute to the limited evidence regarding the association between social isolation and frailty among community-dwelling older adults. Interventions targeting social isolation hold potential for preventing frailty.

Abbreviations

HR|	Hazard ratio
RRR	Relative risk ratio
CI	Confidence interval
FI	Frailty index
SD	Standard deviation
PYs	Person-years
SI	Social isolation
SE	Standard error
NSI	Non-social isolation

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22596-5.

Supplementary Material 1

Acknowledgements

We gratefully thank the CLHLS research team at the Peking University of Healthy Aging and Development (http://chads.nsd.pku.edu.cn) for providing the publicly available dataset.

Author contributions

YZ, JYW, and YFY designed the study. XCL, JZ, LYH, GBH, SYL, DS, JL, QQN, CC, and YYC contributed to the literature search. YZ, WT, LX, XYX, FFH, DL, and GRC supervised the study. JYW and YFY performed the sample acquisition and data collection; JYW and YFY performed the data analysis; YZ, JYW, YFY, LX and XYX interpreted the results of the analysis. YZ, JYW and YFY wrote the original manuscript; YZ, WT, LX, XYX, FFH, DL, and GRC reviewed and edited the manuscript. YZ and WT acquired funding and administered the project. All the authors have read and contributed to the manuscript.

Funding

This study was partly supported by the National Natural Science Foundation of China (82071272, 82171491, and 72174159).

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The biomedical ethics committee of Peking University approved the study (IRB00001052-13074), and all participants or their legal guardians provided written informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Received: 17 June 2024 / Accepted: 2 April 2025
Published online: 16 May 2025

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