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Sex-specific transitions of frailty states and modifiable determinants in community-dwelling older adults: a 16-year Chinese nationwide cohort study

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Abstract

Background

Evidence on sex differences in transitions of frailty states remains inconclusive. This study therefore aimed to analyze sex-specific transitions in frailty states and their modifiable determinants in older Chinese adults.

Methods

We analyzed data from the Chinese Longitudinal Healthy Longevity Survey (CLHLS) collected between 2002 and 2018. Frailty states were characterized using a frailty index. A multi-state Markov model was used to estimate transition intensities, probabilities, and mean sojourn times between states, and to assess the impact of demographic, social, and lifestyle factors on these transitions.

Results

The study included 8,445 participants (mean age 82.62 ± 10.64 years; 50.18% male). The median follow-up time was 6.02 years (IQR: 2.59–9.12). Men had a lower likelihood of transitioning from robust to pre-frail (transition intensity: 0.229, 95% CI: 0.215–0.243) than women (0.297, 95% CI: 0.279–0.316). However, men were more likely to revert from pre-frail to robust (0.170, 95% CI: 0.155–0.188) compared to women (0.137, 95% CI: 0.125–0.151). In contrast, the transition intensities between pre-frail and frail states were comparable between sexes. Furthermore, the determinants of frailty states transitions differed by sex: lifestyle factors (exercise and dietary patterns) were primary influencers in men, whereas social determinants (education level, social participation, and marital status) played a more prominent role in women.

Conclusions

Frailty states transition in late life follows distinct, sex-specific pathways shaped by differential exposure to modifiable risks. To promote healthy aging, sex-specific public health strategies are recommended, focusing on behavioral interventions for men and enhanced social support for women.

Introduction

With the accelerated aging process of the global population, frailty has emerged as a critical public health challenge worldwide. Frailty is a medical syndrome with multiple causes and contributing factors, characterized by a decline in the functioning of multiple physiological systems along with increased sensitivity to stressors [1, 2]. Globally, the pooled prevalence rate of frailty in older people is estimated to be 11%, and 10% in China [3, 4]. Frailty leads to personal disability, falls, dementia, reduced quality of life, and death, but also long-term socioeconomic burdens [2].

Frailty is not a static trait but a dynamic clinical syndrome characterized by reversible transitions between robust, pre-frail, and frail states [2, 5]. This dynamic nature provides a critical window for early intervention. However, current evidence on the determinants of these transitions remains inconsistent, particularly regarding the role of

sex. Some studies indicate that women are more likely to experience improvements or deteriorations in frailty states [5, 6], while others suggest that men are more prone to such changes [7, 8], and some reports find no significant sex differences [9]. Notably, the majority of this evidence originates from Western high-income societies.

This evidence gap is significant because sex, as a socially constructed variable, profoundly influences exposure pathways to various diseases and the distribution mechanisms of risk factors [10]. China, with the world's largest aging population and distinct traditional gender norms, offers a crucial social context for further exploration of this issue. Within the sociocultural environment of China, older men and women often occupy different social spheres, which may channel risk factors through divergent pathways to health. A recent study on sex differences in mortality risk among the Chinese population supports this pattern, indicating that women's health is more influenced by social factors, whereas men's health is more driven by unhealthy lifestyle behaviors [11].

Therefore, this study aims not only to document sex differences but to elucidate the sex-divergent pathways linking modifiable factors to frailty states transitions. We hypothesize that among older Chinese adults, frailty states transitions are primarily driven by lifestyle factors in men and by social determinants in women. To test this hypothesis, we employ a multi-state Markov model, which offers distinct advantages in characterizing the dynamic progression of chronic diseases—enabling estimation of transition intensities and probabilities between states, mean sojourn times in each state, and identification of key drivers of specific transition pathways [12–15]. Using nationally representative longitudinal data from the Chinese Longitudinal Healthy Longevity Survey (CLHLS), this study applies a multi-state Markov model to provide empirical evidence for developing precise, sex-sensitive intervention strategies to promote healthy aging.

Methods

Study population

The population for this study was derived from the CLHLS conducted by Peking University and Duke University. A comprehensive overview of the CLHLS study has been provided in previous studies [16]. In brief, since 1998, the CLHLS has randomly selected community residents aged ≥ 65 years in 23 of 31 provinces, covering approximately 85% of China's population. Its purpose is to collect comprehensive individual-level data on a range of factors to fill the current gaps in scientific research and policy analysis on healthy ageing in China. The CLHLS study was approved by the Research Ethics Committee of Peking University and Duke University (IRB00001052-13074). Written informed consent was obtained from all participants or their legal representatives.

The present study utilized data from the CLHLS, collected between 2002 and 2018. The inclusion criteria were as follows: (1) participants aged 65–105 years; (2) FI missing data in each survey at baseline and follow-up of < 20%; and (3) surveyed at least twice between 2002–2018; (4) no frailty at baseline (FI < 0.25). The exclusion criteria were as follows: (1) participants aged < 65 or > 105 years; (2) FI missing data in each survey at baseline and follow-up ≥ 20%; (3) only one survey data; and (4) frailty at baseline (FI ≥ 0.25). Finally, 8,445 participants were included in this study. A flowchart illustrating the participant selection process is shown in Appendix p9.

FI

The FI was constructed in accordance with standard procedures [17, 18]. Referring to previous studies [19, 20], 40 health variables were selected for this study, including mental health indicators (5 items), activities of daily living (6 items), instrumental activities of daily living (8 items), physical function limitations (6 items), sensory functions (2 items), cognitive functions (1 item), chronic diseases (10 items), and subjective and objectively evaluated functioning (2 items). Each health variable was assigned a value between 0.00 and 1.00, with 0.00 indicating no health defects and 1.00 indicating the presence of health defects (Appendix p4). The scores of the 40 health variables were summed and divided by the theoretical maximum score of 40 points. The resulting score was used as the FI for each participant, ranging from 0 to 1. As the proportion of missing data for all items was < 10%, and the effectiveness and stability of median interpolation are not inferior to the complex missing data filling methods [21, 22], this study employed the median of the corresponding items to impute the missing data, thereby maximizing the sample size. Based on previous studies [2, 23, 24], three frailty states were defined: (1) robust: FI < 0.1; (2) pre-frail: FI between 0.1 and 0.25; and (3) frail: FI ≥ 0.25.

Covariate

In accordance with the findings of previous study [20], the potential influence of various factors, including demographic characteristics, social determinants, and lifestyle factors on the transition of frailty was investigated. Demographic characteristics included age. Socioeconomic determinants included the level of education (0 years of education/≥1 years), residence (urban/rural), marital status (married/other, other includes divorced, widowed or never married) and social participation (yes/no). Lifestyles included smoking status (current/never), current drinking (yes/no), dietary pattern (unfavorable/intermediate or favorable), exercise (yes/no), and body mass index (BMI, < 18.5 or ≥ 28 kg/m^2/ ≥18.5 to < 28 kg/m^2). Detailed information on covariates is available in Appendix p11.

Statistical analysis

Multiple imputations were used to fill in missing covariates. Categorical variables were expressed as frequency (%), and continuous variables were expressed as mean and standard deviation (SD) or median and interquartile range. The c^2 test was used for categorical variables, and analysis of variance or the Kruskal–Wallis test was used for continuous variables to compare the differences in risk factors between the sexes.

In this study, participants' states were categorized as robust, pre-frail, frail, and deceased, with death being an absorbing state and the other states being transient. The following possible state transition paths were considered: remaining unchanged: robust→robust, pre-frail→pre-frail, frail→frail; deteriorating transitions: robust→pre-frail, pre-frail→frail; recovering transitions: pre-frail→robust, frail→pre-frail; transitions to death: robust→deceased, pre-frail→deceased, frail→deceased. A schematic diagram is provided in Appendix p10. In this study, transitions from robust to frail and from frail to robust were not allowed. The reasons for this are based on previous research findings: (1) pre-frail individuals are more likely to transition to robust than frail individuals; (2) transitions from robust to frail or from frail to robust are rare, with probabilities of approximately 3–4% [5].

A multi-state Markov model was used to calculate transition intensities between different frailty states, estimate transition probabilities between different frailty states over specific time periods, estimate the mean sojourn time in each frailty states for individuals, and assess the effects of covariates on transitions between different frailty

states. The covariates included in the model were age (continuous variable), education level, residence, marital status, social participation, smoking status, current drinking, dietary pattern, exercise, and BMI. Covariates were measured at baseline and treated as time-fixed variables. Detailed information on the multi-state Markov model is provided in Appendix p12.

The R4.4.1 msm package was used to construct the multi-state Markov model [25]. Additional analyses were conducted using SAS version 9.4. A two-tailed *P*-value of < 0.05 was considered statistically significant.

Results

Baseline characteristics of study population

This study included 8,445 participants, with a mean age of 82.62 ± 10.64 years, of whom 50.18% were man. The median follow-up time was 6.02 years (IQR: 2.59–9.12). Statistically significant differences were observed between man and woman for most risk factors, including age, education level, marital status, social participation, smoking, drinking, dietary patterns, exercise, and BMI (Table 1).

Table 1
Baseline characteristics of the study population

	All (n = 8445)	Men (n = 4238)	Women (n = 4207)	*P value*
Age (years), mean ± SD	82.62 ± 10.64	81.72 ± 10.04	83.52 ± 11.13	< 0.0001
Social determinants				
Education level (years of schooling)				< 0.0001
Ever (≥ 1)	3737 (44.25)	2877 (67.89)	860 (20.44)	
None (0)	4708 (55.75)	1361 (32.11)	3347 (79.56)	
Residence				0.40
Urban	3716 (44.00)	1884 (44.45)	1832 (43.55)	
Rural	4729 (56.00)	2354 (55.55)	2375 (56.45)	
Marital status				< 0.0001
Married	3208 (37.99)	2182 (51.49)	1026 (24.39)	
Other	5237 (62.01)	2056 (48.51)	3181 (75.61)	
Social participation				< 0.0001
Yes	7117 (84.27)	3721 (87.80)	3396 (80.72)	
No	1328 (15.73)	517 (12.20)	811 (19.28)	
Lifestyle				
Smoking status				< 0.0001
Current	5414 (64.11)	1756 (41.43)	3658 (86.95)	
Never	3031 (35.89)	2482 (58.57)	549 (13.05)	
Current drinking				< 0.0001
Yes	2079 (24.62)	1539 (36.31)	540 (12.84)	
No	6366 (75.38)	2699 (63.69)	3667 (87.16)	
Dietary pattern				< 0.0001
Favorable	2540 (30.08)	1479 (34.90)	1061 (25.22)	
Intermediate/ unfavorable	5905 (69.92)	2759 (34.90)	3146 (74.78)	
Exercise				< 0.0001
Yes	3475 (41.15)	2038 (48.09)	1437 (34.16)	
No	4970 (58.85)	2200 (51.91)	2770 (65.84)	
Values are numbers (percentages) unless stated otherwise*				

	All (n = 8445)	Men (n = 4238)	Women (n = 4207)	*P value*
BMI (kg/m^2)				< 0.0001
18.5 ~ 28	4705 (55.71)	2538 (59.89)	2167 (51.51)	
< 18.5 or ≥ 28	3740 (44.29)	1700 (40.11)	2040 (48.49)	
Values are numbers (percentages) unless stated otherwise*				

At baseline, a higher proportion of men were robust (59.20% vs. 40.80%), while more women were pre-frail (58.68% vs. 41.32%). By the end of the follow-up period, men still had higher proportion in the robust (60.76% vs. 39.24%) and deceased states (54.18% vs. 45.82%), but lower proportion in the pre-frail (45.62% vs. 54.38%) and frail states (36.36% vs. 63.64%) compared to women (Table 2). Throughout the follow-up period, men had higher rates of maintaining robustness, recovering from pre-frailty, and transitioning to death from any state, but lower rates of deterioration (Appendix p6).

Table 2
Frailty states transition statistics

States	Men		Women	
	Initial checkup	Final checkup	Initial checkup	Final checkup
Robust	2478 (59.20%)	96 (60.76%)	1708 (40.80%)	62 (39.24%)
Pre-frail	1760 (41.32%)	99 (45.62%)	2499 (58.68%)	118 (54.38%)
Frail	0 (0.00%)	60 (36.36%)	0 (0.00%)	105 (63.64%)
Death	0 (0.00%)	188 (54.18%)	0 (0.00%)	159 (45.82%)
Total	4238 (50.18%)	443 (49.94%)	4207 (49.82%)	444 (50.06%)

Estimated mean sojourn time and transitions intensity

Model estimates showed men had a longer mean sojourn time in the robust state than women (2.77 vs. 2.02 years), but shorter times in pre-frail (1.99 vs. 2.13 years) and frail states (2.09 vs. 2.66 years) (Fig. 1A-B).

Analysis of transition intensities indicated that men were less likely to transition from robust to pre-frail (0.229, 95% CI 0.215–0.243) compared to women (0.297, 95% CI 0.279–0.316), but more likely to revert from pre-frail to robust (0.170, 95% CI 0.155–0.188) than women (0.137, 95% CI 0.125–0.151). Furthermore, men were consistently more likely to transition from all states to death. However, the likelihood of transitions between pre-frail and frail states was comparable between sexes (Fig. 1A-B).

Estimated mean sojourn times (95% CIs) for each state and transitions intensities (95% CIs) between different frailty states are presented for men (A) and women (B). Arrow colors indicate transitions between states: black indicates maintenance of the current state, red indicates worsening of the condition or death, and blue indicates recovery to a healthier state. The bold values indicate a higher transition intensity for this specific pathway in the current gender compared to the other gender.

Transitions probabilities of frailty states

Figure 2 illustrates the dynamic transition probabilities over 16-years. The analysis reveals that the probability of remaining in the same state consistently decreased over time in both sexes (Figs. 2A–C), whereas the probability of death showed a continuous increasing trend, with men consistently exhibiting higher mortality probabilities than women across all states (Figs. 2H–J).

Transition probabilities for both deterioration and recovery pathways peaked around the first three years of follow-up and then declined. Sex-based differences followed a similar pattern, widening initially and then narrowing. In the first three years, men had lower probabilities of deteriorating (robust→pre-frail: 15.2%→21.8% vs. 20.0%→29.1%; pre-frail→frail: 12.0%→13.9% vs. 13.0%→17.1%) and a higher probability of recovering from pre-frail to robust (11.3%→16.2% vs. 8.3%→10.9%), but a lower probability of recovering from frail to pre-frail (8.2%→9.5% vs. 8.2%→11.0%) (Fig. 2D-G). Original data are in Appendix p7.

The figure displays the transition probabilities of frailty states for older men and women at follow-up years 1, 2, 3, 4, 5, 6, 9, 12, and 16. The blue and yellow lines represent men and women, respectively.

Covariate effects on frailty states transitions

Increasing age elevated the risk of deterioration and reduced the likelihood of recovery for both sexes (Table 3). For modifiable factors, distinct sex-specific patterns emerged:

In men, lack of exercise (HR = 1.393, 95% CI: 1.199–1.619) and an intermediate or unfavorable dietary pattern (HR = 1.299, 95% CI: 1.124–1.501) significantly increased the risk of progression from robust to pre-frail. Notably, current drinking (HR = 1.257, 95% CI: 1.003–1.575) and lack of exercise (HR = 1.595, 95% CI: 1.265–2.010) were associated with an increased likelihood of reverting from pre-frail to robust (Table 3).

In women, lack of formal education (HR = 1.275, 95% CI: 1.065–1.526) and social participation (HR = 1.425, 95% CI: 1.110–1.828) were significantly associated with an increased risk of transitioning from robust to pre-frail. Conversely, a change in marital status (e.g., widowed) was associated with a higher likelihood of recovery from frail to pre-frail (HR = 1.607, 95% CI: 1.018–2.536) (Table 3).

In the transition from pre-frail state to death, men were primarily influenced by social participation and BMI, whereas women were more associated with marital status and social participation. In the progression from frail state to death, education level was the main influencing factor for men, while place of residence played a more significant role for women (Table 3). Furthermore, the analysis of covariates related to the transition from robust state to death is provided in Appendix P8.

Table 3
Effects of covariates on transitions among frailty states

Covariate	Level	Hazard Ratio (95% CI)					
		Deteriorate transitions		Recovery transitions		Death transitions	
		Robust → Pre-frail	Pre-frail → Frail	Pre-frail → Robust	Frail → Pre-frail	Pre-frail → Deceased	Frail → Deceased
Age							
Men	—	**1.047 (1.038, 1.056)**	**1.041 (1.027, 1.055)**	**0.966 (0.951, 0.981)**	0.981 (0.934, 1.030)	**1.067 (1.057, 1.078)**	**1.015 (1.003, 1.026)**
Women	—	**1.059 (1.048, 1.070)**	**1.050 (1.041, 1.059)**	**0.991 (0.975, 1.007)**	**0.963 (0.938, 0.988)**	**1.064 (1.055, 1.072)**	**1.031 (1.022, 1.041)**
Social determinants							
Education level							
Men	None (0)	1.294 (0.961, 1.327)	0.866 (0.713, 1.050)	0.879 (0.699, 1.105)	1.150 (0.650, 2.034)	0.943 (0.795, 1.118)	**1.226 (1.013, 1.484)**
Women	None (0)	**1.275 (1.065, 1.526)**	1.111 (0.907, 1.360)	1.000 (0.771, 1.297)	1.051 (0.598, 1.846)	1.0423(0.827, 1.313)	1.005 (0.798, 1.265)
Residence							
Men	Rural	1.064 (0.917, 1.235)	0.812 (0.616, 1.070)	0.984 (0.728, 1.329)	0.863 (0.485, 1.534)	0.980(0.823, 1.166)	1.083 (0.890, 1.319)
Women	Rural	1.075 (0.917, 1.261)	0.990 (0.846, 1.159)	0.976 (0.777, 1.227)	1.446 (0.931, 2.246)	1.053 (0.894, 1.240)	**1.224 (1.037, 1.444)**
Marital status							
Men	Other	1.077 (0.920, 1.261)	1.109 (0.915, 1.344)	1.201 (0.939, 1.537)	0.961 (0.552, 1.673)	**1.349 (1.132, 1.607)**	1.044 (0.861, 1.267)
Women	Other	0.867 (0.737, 1.021)	1.104 (0.918, 1.327)	0.863 (0.685, 1.088)	**1.607 (1.018, 2.536)**	**1.398 (1.099, 1.777)**	1.088 (0.869, 1.363)
Social participation							
Men	No	1.347 (0.954, 1.902)	1.029 (0.715, 1.482)	1.351 (0.863, 2.116)	1.565 (0.632, 3.876)	**1.473 (1.188, 1.828)**	0.916 (0.662, 1.267)

Covariate	Level	Hazard Ratio (95% CI)					
		Deteriorate transitions		Recovery transitions		Death transitions	
		Robust → Pre-frail	Pre-frail → Frail	Pre-frail → Robust	Frail → Pre-frail	Pre-frail → Deceased	Frail → Deceased
Women	No	**1.425 (1.110, 1.828)**	1.101 (0.884, 1.373)	1.227 (0.875, 1.720)	1.582 (0.968, 2.586)	**1.328 (1.102, 1.599)**	0.830 (0.674, 1.022)
Lifestyle							
Smoking status							
Men	Current	1.021(0.884, 1.179)	0.957 (0.791, 1.159)	0.899 (0.718, 1.126)	0.985 (0.566, 1.714)	1.050 (0.887, 1.243)	1.046 (0.866, 1.264)
Women	Current	0.875 (0.705, 1.086)	0.891 (0.716, 1.108)	0.756 (0.546, 1.047)	0.614 (0.295, 1.277)	1.330 (1.076, 1.644)	1.076 (0.850, 1.363)

Table 3
Effects of covariates on transitions among frailty states (continued)

Covariate	Level	Hazard Ratio (95% CI)					
		Deteriorate transitions		Recovery transitions		Death transitions	
		Robust → Pre-frail	Pre-frail → Frail	Pre-frail → Robust	Frail → Pre-frail	Pre-frail → Deceased	Frail → Deceased
Lifestyle							
Current drinking							
Men	Yes	1.125 (0.973, 1.300)	1.170 (0.961, 1.423)	**1.257 (1.003, 1.575)**	1.412 (0.834, 2.391)	0.863 (0.723, 1.031)	1.145 (0.948, 1.382)
Women	Yes	0.977 (0.766, 1.244)	0.809 (0.637, 1.027)	1.198 (0.849, 1.689)	1.161 (0.618, 2.181)	0.955 (0.770, 1.184)	0.944 (0.745, 1.196)
Exercise							
Men	No	**1.393 (1.199, 1.619)**	0.861 (0.707, 1.049)	**1.595 (1.265, 2.010)**	1.229 (0.686, 2.201)	**1.263 (1.056, 1.511)**	0.926 (0.762, 1.125)
Women	No	1.126 (0.958, 1.325)	1.016 (0.864, 1.194)	0.944 (0.745, 1.197)	1.302 (0.829, 2.046)	1.050 (0.872, 1.264)	0.997 (0.836, 1.188)
Dietary pattern							
Men	Intermediate/ Unfavorable	**1.299 (1.124, 1.501)**	1.091 (0.897, 1.328)	1.096 (0.875, 1.374)	1.421 (0.800, 2.524)	0.999 (0.828, 1.204)	1.146 (0.936, 1.402)
Women	Intermediate/ Unfavorable	1.044 (0.884, 1.233)	0.980 (0.822, 1.170)	0.961 (0.748, 1.236)	0.959 (0.599, 1.532)	1.007 (0.830, 1.221)	1.019 (0.842, 1.234)
BMI							
Men	< 18.5 or ≥ 28 kg/m^2	0.911 (0.788, 1.053)	0.914 (0.759, 1.101)	0.822 (0.653, 1.036)	1.130 (0.693, 1.843)	**1.435 (1.219, 1.689)**	0.956 (0.792, 1.153)
Women	< 18.5 or ≥ 28 kg/m^2	1.027 (0.883, 1.195)	1.061 (0.912, 1.234)	1.088 (0.876, 1.351)	1.214 (0.834, 1.766)	**1.304 (1.108, 1.534)**	0.963 (0.820, 1.130)

Reference of covariates: education level, ref = ever (≥ 1); residence, ref = city and town; marital status, ref = married; smoking status, ref = never; current drinking, ref = no; dietary pattern, ref = favorable; exercise, ref = yes; social participation, ref = yes; BMI, ref = 18.5 ~ 28 kg/m^2.

Boldface indicates statistical significance ($P < 0.05$).

Discussion

Our 16-year nationwide cohort study reveals two principal findings. First, there are significant sex differences in the dynamic patterns of frailty state transitions: women have a higher risk of progressing from robust to pre-frail, whereas men show a greater propensity for recovery from pre-frail to robust, yet face a significantly higher mortality risk once in a pre-frail or frail state. Second, and more importantly, the pathways influencing these transitions are sexually divergent. Transitions in men are predominantly driven by modifiable lifestyle factors (physical activity and diet), while transitions in women are more strongly associated with social determinants (education, social participation, and marital status). This supports our primary hypothesis and underscores that frailty progression is channeled through distinct, gender-shaped pathways.

Sex-specific transition patterns in frailty states

The systematic review by Kojima et al. [5] and an Italian study [6] both reported that women were more likely to experience transitions in frailty states, whether toward improvement or deterioration. In contrast, a German study presented contradictory findings, indicating that men were more prone to transitions toward deterioration [7], A multinational European study yielded results partially consistent with ours, observing that men were less likely to enter a frailty trajectory at a healthy baseline but faced a higher mortality risk once frailty had developed [8]. However, a key difference lies in the finding of that European study, which reported that men had a higher risk of progressing from pre-frail to frail state [8], whereas our study demonstrated that women exhibited higher probabilities of bidirectional transitions between pre-frail and frail states. It is noteworthy that the intrinsic transition intensities between these states were similar between sexes in our study, suggesting that the observed probability differences may be attributed to a competing risk effect. Specifically, the higher mortality among men in pre-frail or frail states may have shortened their observation time, thereby reducing opportunities for further state transitions.

These variations in transition patterns of frailty states across populations may stem from complex physiological mechanisms and context-specific sociocultural factors. In the Chinese context, women generally have a longer life expectancy than men [26], which may extend their exposure window to frailty-related risks. Meanwhile, men tend to engage more frequently in health-risk behaviors [11], which may contribute to their elevated mortality risk once a frailty trajectory has been initiated.

Sex differences in risk factor of frailty state transitions

Social determinants [22, 27–31]and lifestyle factors [28, 32–34] have been established as significant risk factors for frailty. Building on this foundation, our study further investigates the differential impacts of these factors on transitions of frailty states between men and women. The analysis reveals that transitions of frailty states in men are primarily driven by exercise and dietary patterns, mainly affecting their progression from robust to pre-frail. In contrast, women's frailty states transitions were more significantly associated with social determinants. Specifically, lower education levels and lack of social participation increased women's risk of progressing from robust to pre-frail states, while changes in marital status such as widowhood or divorce promoted recovery from frail to pre-frail states. Recent research has also found that socioeconomic status is exclusively associated with increased frailty risk in women [35]. The observed association between marital loss and frailty recovery in women aligns with previous findings that older women who lose partners may experience lower frailty probability [36, 37]., possibly due to reduced caregiving burdens or shifts in social roles.

These sex-based differences likely mirror traditional gender norms in Chinese society, where women have historically been oriented toward domestic spheres and men toward public life, thereby shaping distinct exposure pathways to health risks and resources.

Implications for practice and public health

These findings underscore the necessity of incorporating a gender perspective into public health strategies and clinical interventions by implementing targeted approaches: prioritizing the management of risk behaviors in men, while strengthening socioeconomic support and enhancing quality of life for women. Furthermore, this study reveals that the mean sojourn time in each frailty state among older adults is only about two years, and the transition probabilities between frailty states—as well as sex-based differences—are most pronounced during the initial follow-up period, particularly within the first three years. Therefore, it is crucial to implement routine frailty screening in the overall older population and maintain heightened vigilance during this early stage.

The primary strength of this study lies in its use of 16-year nationwide longitudinal data and the application of a multi-state model, which uniquely captures the complete dynamic process of frailty transitions. However, this study also has several limitations. First, reliance on self-reported data may introduce bias, and treating covariates as time-fixed ignores potential changes over the long follow-up period. Second, certain findings, such as the association between alcohol consumption or lack of exercise and recovery from frailty among men, should be interpreted with caution. These results may reflect reverse causality (e.g., recent recovery leading to reduced physical activity), self-report bias, or complex behavioral patterns—although previous studies have reported an association between the highest level of alcohol consumption and the lowest risk of frailty [38]. Finally, most covariates exhibited primarily unidirectional effects (influencing either the progression or recovery of frailty states), which may be because deterioration is inherently more common than recovery in older populations [5]. The relatively low incidence of recovery events may also have resulted in limited statistical power due to insufficient sample size, making it difficult to detect statistically significant associations.

Conclusion

This study demonstrates that frailty transitions in late life are not governed by a universal set of risk factors but are channeled through pathways shaped by lifelong gender socialization. By identifying lifestyle factors as key levers for men and social determinants as critical points of entry for women, our research provides a scientific blueprint for developing precise and effective interventions to mitigate the burden of frailty in China's aging population.

Declarations

Clinical trial number: not applicable.

Contributors: XL contributed to the acquisition and analysis of data, and writing of the original draft. TY contributed to the manuscript reviewing and editing efforts. HH gave final approval of the version to be published, and agreed to be accountable for all aspects of the work. All authors read and approved the final manuscript.

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Data sharing statement: CLHLS data are available via the website: https://opendata.pku.edu.cn/ (accessed on 1 December 2021).

Declaration of interests: We have no conflict of interest to declare.

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Figures

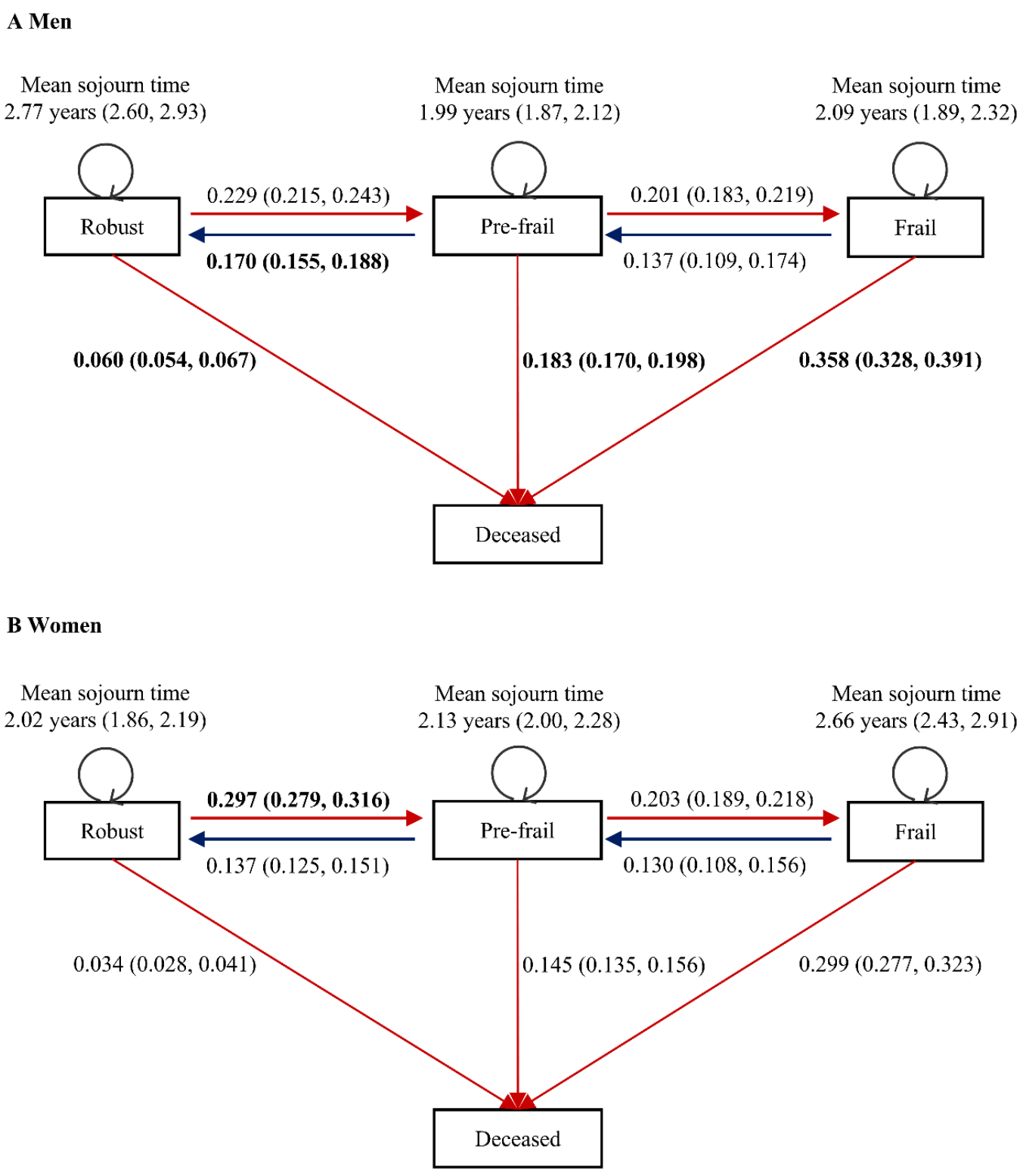


Figure 1

Transitions intensity between different frailty states by gender

Estimated mean sojourn times (95% CIs) for each state and transitions intensities (95% CIs) between different frailty states are presented for men (A) and women (B). Arrow colors indicate transitions between states: black indicates maintenance of the current state, red indicates worsening of the condition or death, and blue indicates

recovery to a healthier state. The bold values indicate a higher transition intensity for this specific pathway in the current gender compared to the other gender.

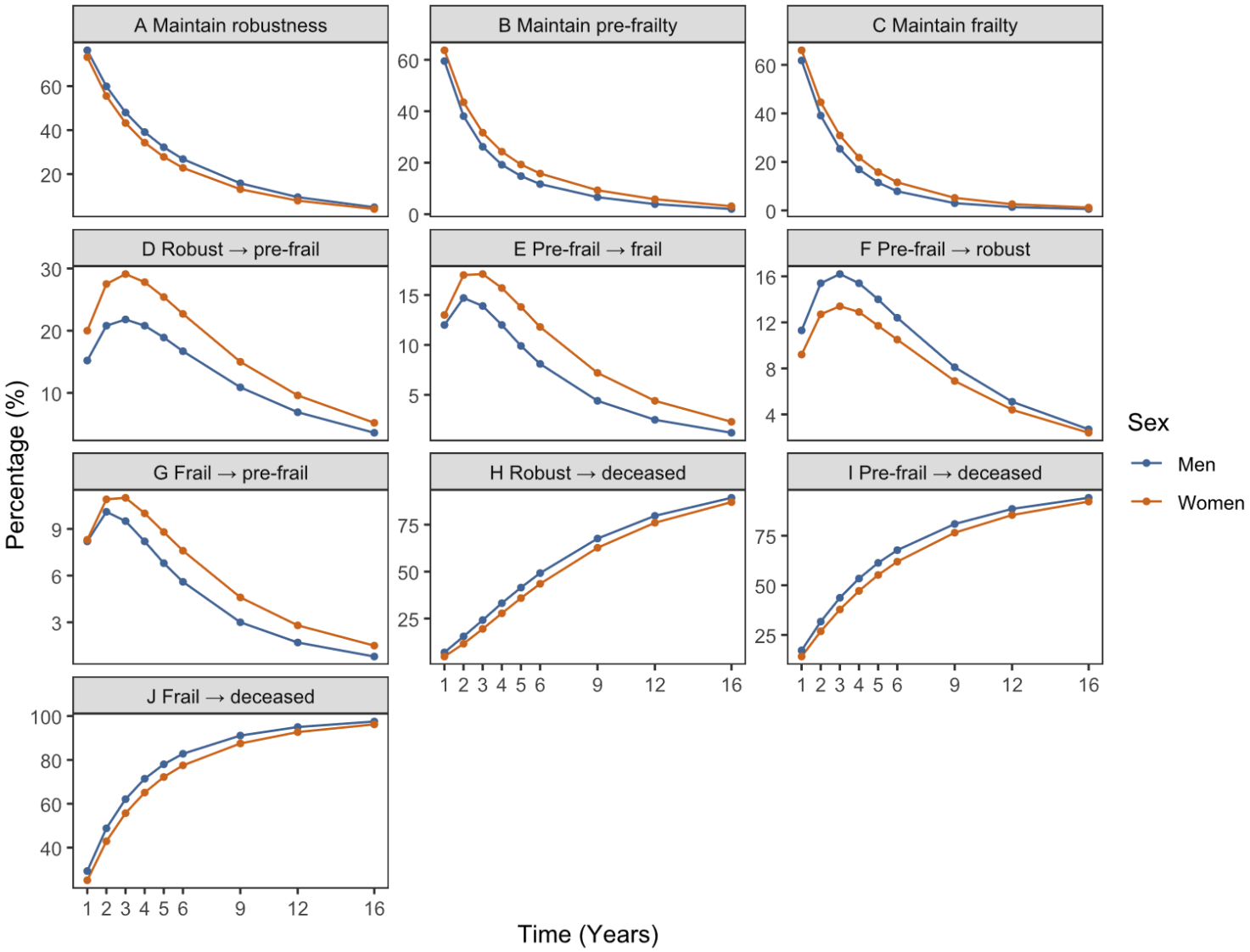


Figure 2

Possible transition states of frailty and corresponding transition probabilities at 1-6, 9, 12, and 16 years, stratified by sex

The figure displays the transition probabilities of frailty states for older men and women at follow-up years 1, 2, 3, 4, 5, 6, 9, 12, and 16. The blue and yellow lines represent men and women, respectively.

Supplementary Files

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- Appendix.pdf