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Heterogeneous Trajectory of Frailty and Associated Factors among the Middle-Aged and Older People: Evidence from CHARLS 2011-2020

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Abstract: This study aims to investigate the heterogeneity in the developmental trajectories of frailty and to identify associated influencing factors among middle-aged and older adults. Based on China Health and Retirement Longitudinal Study database from 2011 to 2020. This study selected survey data from 9, 442 individuals 45 years and older. Then constructed a latent growth mixture model to identify the trajectories of frailty development, screened for associated factors using health ecological model, and analyzed through multiple stepwise logistic regression. The heterogeneous trajectories of frailty among the middle-aged and older people could be divided into four categories: "C1: Rapid increase (10.14%)", "C2: Slow decline (7.60%)", "C3: Persistent high (11.09%)", "C4: Stable low (71.17%)". Female, aged ≥60 years, disability, obesity, short sleep duration, lack of social activity, rural residence, mid-western region, illiteracy, previously employed, and low-income were identified as the primary risk factors for frailty. Living alone significantly increases the risk of transitioning to the "C1 Rapid increase" group. Conversely, aged 45-59 years, normal BMI, eastern region, being working and having a more satisfying life were protective factors for the "C2: Slow decline" group. (all $P<0.05$). There is significant heterogeneity in the developmental trajectory of frailty in the middle-aged and older people. It is recommended to identify and implement targeted frailty management as early as possible based on the characteristics of different groups, to effectively prevent or delay the deterioration of frailty in the middle-aged and older people.

1. Introduction

As the global trend of population aging accelerates, research on the health of middle-aged and older people is growing. Frailty, as a geriatric syndrome closely related to ageing, has become an important new indicator for assessing the health status of this group. Frailty is mainly characterized by a decline in physiological functions and psychological adaptability [1]. It not only significantly

increases the risk of various adverse health outcomes, such as falls, disability and death [1-3], affecting the physical and mental health and quality of life of middle-aged and older people, but also leads to additional consumption of healthcare resources and increased family burden [4]. Therefore, the management of frailty has become a crucial component in achieving healthy aging, and its assessment and intervention are continuing to receive widespread attention. Recent studies have shown that the onset and progression of frailty is influenced by a variety of factors, including age, lifestyle, depression, physical activity, and cognitive function [5,6]. Furthermore, frailty is a dynamic and reversible process, and early identification and targeted intervention of relevant factors is essential for effectively preventing and delaying its progression [6,7]. However, studies on frailty have focused mainly on the older population aged 60 years and older, are mostly based on cross-sectional data, with less attention to changes in frailty during follow-up, and tend to ignore the heterogeneity of the potentially changing population.

The Latent Growth Mixture Modeling (LGMM) is a longitudinal data analysis method that is employed to elucidate underlying trends in time-series data and to permit the investigation of discrepancies in individual developmental trajectories [8]. It can be used to examine the process of decline and its specific manifestations in different subgroups in greater detail. The Health Ecological Model (HEM) posits that an individual's health status is influenced by a complex interplay of factors, including personal attributes, interpersonal networks, and the social environment. This model has gained prominence in analyzing of the factors influencing individual health and disease outcomes [9,10]. Based on this model it is possible to comprehensively consider the various factors influencing frailty, leading to the development of more comprehensive and effective preventive and control measures. Therefore, this study expands the age range to include middle-aged and older people (≥45 years of age), and utilizes the LGMM to deeply explore the heterogeneous trajectories of frailty in order to more accurately understand the developmental process and individual differences of frailty. At the same time, we conduct a comprehensive and systematic analysis of the factors influencing the developmental trajectory of frailty based on the five dimensions of the HEM. The goal is to investigate the heterogeneity of the developmental trajectories of frailty and associated factors of middle-aged and older people, to improve the health of this population and to achieve healthy aging.

2. Methods

2.1. Data

The data for this study come from the China Health and Retirement Longitudinal Study (CHARLS) project. The project uses a multistage sampling design, covering 150 counties (districts) in 28 provinces, involving 450 village-level units and approximately 17,000 respondents, and has completed five survey phases since 2011.The survey covers basic demographic, socio-economic status, health conditions and daily activities of the middle-aged and older people, providing a comprehensive overview of their current situation in China. It is a highly nationally representative longitudinal survey that has been extensively utilized for research across various fields. This data offers substantial support for our in-depth study of the developmental trajectories and influencing factors of frailty in middle-aged and older individuals, and meets the needs of this study.

The CHARLS was approved by the Biomedical Ethics Committee of Peking University (IRB00001052-11015), and informed consent was obtained. This study used baseline data from 2011 and de-identified follow-up data from 2013, 2015, 2018, and 2020. Participants aged ≥45 years in 2011 who completed all four follow-up surveys were included. Individuals with >30% missing data on the Frailty Scale were excluded. Ultimately, 9,442 valid participants were included in the study. The inclusion and exclusion process are shown in Figure 1.

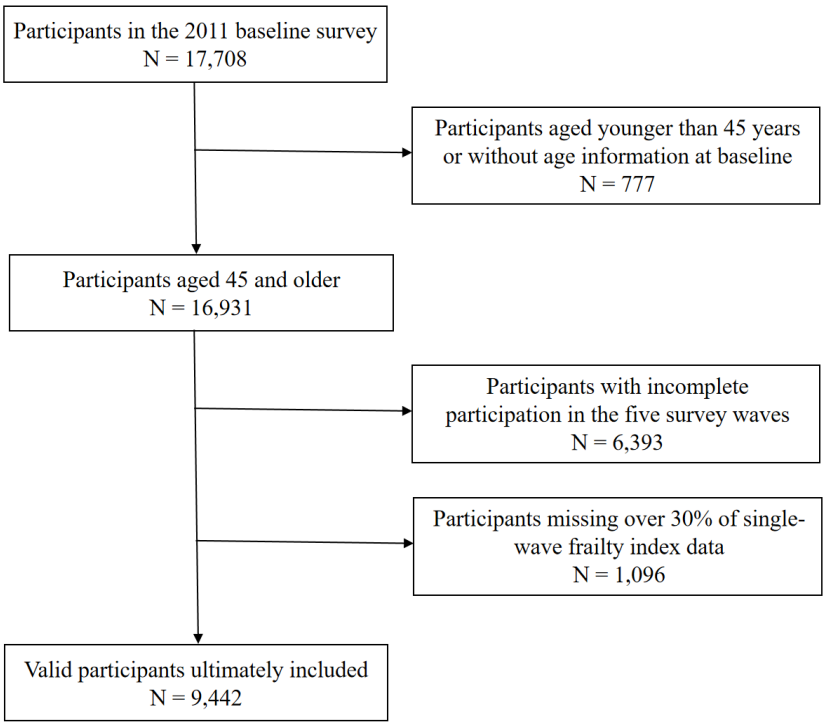

Figure 1: The selection process of participants.

2.2. Research variables

2.2.1. Frailty Index

Frailty index is a widely used assessment tool based on the theory of health deficit principles. It includes multiple domains, such as physical condition, psychological state, and social functioning, allowing for a comprehensive evaluation of frailty [7]. Referring to relevant existing studies, 30 items were selected from the CHARLS database to construct the frailty index. These included 14 chronic diseases (hypertension, dyslipidaemia, diabetes mellitus, malignancy, chronic lung disease, liver disease, heart disease, stroke, kidney disease, gastrointestinal disease, mental and emotional disorders, memory disorders, arthritis and asthma); 2 sensory disorders (vision, hearing problems); 6 basic activities of daily living (dressing, bathing, eating, getting in and out of bed, toileting, and bowel and bladder control); and 5 instrumental activities of daily living (housework, cooking, shopping, money management, medication); 1 self-rated health; 1 depressive symptom (short version of the Centre for Epidemiology and Streamlining Depression Scale CES-D-10); and 1 cognitive function (Telephone Assessment of Cognitive Functioning Questionnaire Revised TICS-m).Cognitive function was a continuous variable scored from 0 to 1, with the remaining items scored 1 for an unhealthy state and 0 otherwise.

The principle of FI is to determine the degree of frailty by calculating the ratio of the number of health defects currently present in an individual to the total number of health defects that could be present [15]. In this study, FI was calculated by dividing the sum of all entry scores by 30 and multiplying by 100, with a range of values from 0 to 100, with larger values indicating more severe debilitation. Consistency with relevant studies [11-14], the classification criteria for debilitation are: $FI \geq 25$ is frailty, $10 < FI < 25$ is pre-frailty, and $FI \leq 10$ is robust.

2.2.2. Influence factors

Based on the HEM and related research [9,10,16] ,20 indicators that may influence the development of frailty in the middle-aged and older population were selected for analysis in this study. These include: (1) personal trait layer: gender, age, disability, Body Mass Index (BMI); (2) behavioral feature layer: smoking, alcohol consumption, physical activity, night's sleep time, nap duration, life satisfaction; (3) networking layer: social activities, marital status, number of family members, place of residence, region of residence; (4) working and living conditions: employment status, education level, annual per capita income; (5) public policy: health insurance, pension insurance. The allocation of the independent variables is shown in Appendix Table A1.

2.3. Statistical analysis

This study used Stata 17.0 to process CHARLS database. Missing baseline demographic data were screened and supplemented using the 2013 database, and remaining missing values were imputed using mean interpolation. Next, we used Mplus8.3 to construct the LGMM of the frailty trajectories in middle-aged and older people. The modeling process began with fitting a single trajectory and gradually increasing the number of trajectories until the optimal model was determined. Model fit was assessed using the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), sample-size adjusted BIC (aBIC), Entropy, Likelihood Ratio Test (LMRT), and Bootstrapped Likelihood Ratio Test (BLRT). The optimal model exhibited lower AIC, BIC, and aBIC values; Entropy values close to 1 (exceeding 0.80); significant LMRT and BLRT results ($P<0.05$); each trajectory class representing at least 5% of the sample; and good interpretability. Finally, a multiple stepwise logistic regression analysis was performed using SPSS 26.0. The optimal latent class classification served as the dependent variable, while the aforementioned influencing factors were used as independent variables. The analysis used a forward stepwise method, maintaining a significance level of $\alpha=0.05$ across all tests.

3. Results

3.1. Frailty progression at each follow-up period

According to Table1, there was a consistent annual decline in the number and proportion of individuals classified as healthy, dropping from 4,058 (42.98%) in 2011 to 2,460 (26.05%) in 2020. The number of the participants in the pre-frail state peaked in 2015 at 4,501 people (47.67%), but then slightly decreased to 3,923 (41.55%) by 2020. In contrast, the number of frail individuals significantly rose from 1,372 (14.53%) in 2011 to 3,059 (32.40%) in 2020.

Table 1: Frailty index of the middle-aged and older people at different follow-up waves.

Year	Robust		Pre-frail		Frail	
	Number	Detection rate (%)	Number	Detection rate (%)	Number	Detection rate (%)
2011	4058	42.98	4012	42.49	1372	14.53
2013	3695	39.13	4243	44.94	1504	15.93
2015	2639	27.95	4501	47.67	2302	24.38
2018	2458	26.03	4134	43.78	2850	30.18
2020	2460	26.05	3923	41.55	3059	32.40

3.2. LGMM latent class analysis of frailty progression

This study sequentially constructed 1 to 5 potential category models. As shown in Tables 2, AIC,

BIC, and aBIC values decreased with more categories, but the rate of decline slowed after four. The four-class model showed significant BLRT and LMRT results ($P < 0.05$), and each class included over 5% of participants. Consequently, based on the rationality of the model fit indices and their practical interpretability, the four-category model was deemed optimal.

Table 2: Fitting results of LGMM for the trajectories of frailty.

Model	AIC	BIC	aBIC	Entropy	LMR	BLRT	Class proportion
1	324 587.272	324 658.801	324 627.023	-	-	-	-
2	323 159.917	323 252.905	323 211.594	0.788	0.001	0.001	21.66%/78.34%
3	322 387.391	322 501.837	322 450.992	0.794	0.001	0.001	15.94%/9.98%/74.08%
4	321 827.406	321 963.312	321 902.933	0.803	0.001	0.001	10.14%/7.60%/11.09%/71.17%
5	321 615.988	321 773.352	321 703.440	0.750	0.001	0.001	56.29%/8.92%/5.69%/19.21%/9.89%

3.3. Heterogeneous trajectories of frailty progression

According to Figure 2 and Table3 the LGMM analysis revealed four heterogeneous trajectories of frailty progression among middle-aged and older people. The first group, with a low baseline mean score on the frailty index (α=13.40, P<0.01), showed a rapid increase (β=2.80, P<0.01), was therefore labeled as “C1: Rapid increase”. The second group, characterized by a higher baseline mean score (α=27.02, P<0.01), displayed a gradual decline (β=–0.46, P<0.01), was labeled as the “C2: Slow decline”. The third group had the highest mean score on the frailty index at baseline (α=28.13, P<0.01), increasing and maintaining the highest mean score (β=1.39, P<0.01) was labeled as “C3: Persistent high”. The fourth group, with the lowest baseline mean score (α=11.33, P<0.01), remained consistently stable (β=0.50, P<0.01), was labeled as “C4: Stable low”. The specific parameters.

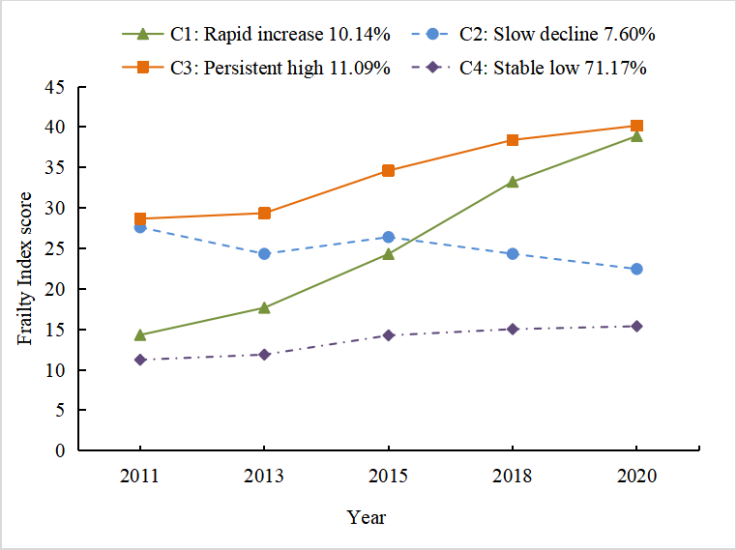

Figure 2: Heterogeneous trajectories of frailty progression.

Table 3: The Intercept and slope estimate of potential categories.

Class		Estimate	S.E	Est./ SE.	P value
Class1	Intercept(I)	13.398	0.381	35.168	<0.001
	Slope(S)	2.801	0.057	48.894	<0.001
Class2	Intercept(I)	27.022	0.461	58.657	<0.001
	Slope(S)	-0.456	0.077	-5.937	<0.001
Class3	Intercept(I)	28.13	0.398	70.713	<0.001
	Slope(S)	1.387	0.050	27.923	<0.001
Class4	Intercept(I)	11.33	0.112	101.506	<0.001
	Slope(S)	0.499	0.013	38.070	<0.001

3.4. Logistic regression analysis of frailty trajectory

The basic characteristics of each group of frailty trajectories are shown in supplemental Table4. Multiple stepwise logistic regression analysis was performed with the four trajectory categories as the dependent variable and the relevant influencing factors as independent variables. Firstly, this study performed with C4 as the reference group. Comparing C1 with C4: individuals who were overweight or obese, no social activity, rural, from western or central regions, and previously employed were more likely to be classified into C1. In contrast, those aged 45-59, without disabilities, sleeping ≥5h, with family sizes of ≥3, with at least an elementary education, and having high incomes were more likely to be classified into C4. Comparing C2 with C4: being obese, not drink alcohol, dissatisfied with their lives, having no social activity, rural, from western or central regions, and previously or never employed were more likely to be classified into C2. On the other hand, male, aged 45-59, without disabilities, sleeping ≥5h, with at least an elementary education, and having high or moderate incomes were more likely to be classified into C4. Comparing C3 with C4: being overweight or obese, not drink alcohol, dissatisfied with their lives, having no social activity, rural, from western or central regions, and previously or never employed were more likely to be classified into C3. On the contrary, male, aged 45-59, without disabilities, sleeping ≥5h, with at least an elementary education, and having high or moderate incomes were more likely to be classified into C4. See Table 4 for detail.

Table 4: Logistic regression analysis for factors associated with frailty trajectory (Ref: C4).

Variable	C1vsC4		C2vsC4		C3vsC4	
	β	OR (95%CI)	β	OR (95%CI)	β	OR (95%CI)
Gender (Ref: Female)						
Male	-0.16	0.86(0.72-1.01)	-0.28	0.78 (0.62-0.92) **	-0.36	0.70(0.59-0.84) ***
Age (Ref: ≥60)						
45-59	-0.35	0.70(0.60-0.82) ***	-0.22	0.80(0.67-0.96) *	-0.51	0.60(0.51-0.70) ***
Disability (Ref: Yes)						
No	-0.25	0.78(0.65-0.94) **	-1.04	0.35(0.30-0.42) ***	-1.07	0.34(0.29-0.40) ***
BMI (Ref: Normal)						
Overweight	0.37	1.44(1.22-1.70) ***	0.11	0.84(0.60-1.17)	0.45	1.56(1.32-1.86) ***
Obese	0.76	2.13(1.74-2.61) ***	0.51	1.67(1.31-2.13) ***	1.06	2.89(2.36-3.54) ***
Alcohol consumption (Ref: Yes)						
No	0.12	1.12(0.94-1.34)	0.32	1.38(1.12-1.71) **	0.31	1.36(1.13-1.65) **
Night's sleep time (Ref:<5h)						
5-9h	-0.24	0.79(0.66-0.95) *	-0.88	0.42(0.35-0.50) ***	-0.79	0.45(0.38-0.54) ***

>9h	-0.60	0.55(0.36-0.83) **	-0.80	0.45(0.30-0.67) ***	-0.81	0.44(0.31-0.64) ***
Life satisfaction (Ref: Satisfied)						
Dissatisfied	-0.25	0.78(0.60-0.82)	0.78	2.18(1.80-2.64) ***	1.04	2.82(2.39-3.33) ***
Social activity (Ref: Yes)						
No	0.26	1.30(1.13-1.50) ***	0.23	1.26(1.07-1.49) **	0.19	1.21(1.05-1.40) *
Number of family members (Ref: 1)						
≥3	-0.42	0.66(0.48-0.89) **	0.01	1.01(0.69-1.48)	-0.13	0.88(0.64-1.22)
Place of residence (Ref: City)						
Countryside	0.42	1.52(1.28-1.80) ***	0.31	1.36 (1.12-1.66) **	0.36	1.44(1.21-1.71) ***
Region of residence (Ref: East)						
West	0.35	1.42(1.19-1.69) ***	0.51	1.66(1.36-2.04) ***	0.71	2.03(1.68-2.45) ***
Central	0.39	1.48(1.25-1.76) ***	0.32	1.38(1.12-1.70) **	0.75	2.12(1.76-2.55) ***
Employment status (Ref: Working)						
Previous	0.34	1.40(1.18-1.66) ***	0.61	1.83(1.52-2.22) ***	0.90	2.46(2.09-2.89) ***
Never	0.42	1.52(0.90-2.55)	0.62	1.86(1.06-3.27) *	0.56	1.75(1.04-2.93) *
Highest level of education (Ref: Uneducated)						
Junior high school and above	-0.67	0.51(0.42-0.63) ***	-0.83	0.44(0.34-0.56) ***	-0.78	0.46(0.37-0.57) ***
Elementary school	-0.32	0.72(0.61-0.85) ***	-0.29	0.75(0.62-0.90) **	-0.43	0.65(0.55-0.77) ***
Annual per capita income (Ref: Low)						
High	-0.19	0.83(0.69-0.99) *	-0.63	0.53(0.42-0.68) ***	-0.65	0.52(0.43-0.64) ***
Moderate	-0.11	0.89(0.74-1.08)	-0.34	0.71(0.57-0.89) **	-0.41	0.66(0.54-0.81) ***

Standard errors in parentheses: * p<0.05, ** p<0.01, *** p<0.001

Then, performed with C3 as the reference group. Comparing C1 with C3: individuals without disabilities, sleeping≥5h, and having high or moderate incomes were more likely to be classified into C1. Conversely, those who were obese, dissatisfied with their lives, had two family members, from western or central regions, and previously employed were more likely to be classified into C3. Comparing C2 with C3: those aged 45-59 were more likely to be classified into C2. In contrast, being overweight or obese, dissatisfied with their lives, from central regions, and previously employed were more likely to be classified into C3. See Appendix Table A2 for detail.

4. Discussion

The objective of this study was to investigate the trajectories of frailty development and their associated influencing factors among middle-aged and older people in China. The results showed that the prevalence of frailty in this population increased significantly from 14.53% in 2011 to 32.40% in 2020, consistent with findings from previous studies [11,12,17]. Further analyzed using the LGMM, we found that the developmental trajectory of frailty can be categorized into four potential categories with heterogeneity: C1: Rapid increase (10.14%), C2: Slow decline (7.60%), C3: Persistent high (11.09%), C4: Stable low (71.17%). The C4 group accounted for the largest proportion, with a stable frailty index and no incidence of frailty throughout the follow-up period. This indicates that the predominant trajectory of frailty development among the Chinese middle-

aged and older people is characterized by a low baseline and stability. The C1 group showed a trend of rapid growth, and individuals in this group deteriorated rapidly from the pre-frailty stage to a more serious state of frailty, necessitating focused observation and intervention. The C3 group although the rate of increase of the frailty index was slower, it still continued to rise over time, and the degree of frailty was gradually aggravated. The above results were consistent with national and international studies [18, 19]. In addition, in line with previous studies, this study also identified a gradual decline trend in the frailty index of the C2 group, with individuals changing from frail to pre-frail states, thereby reaffirming the reversibility of the frailty process and the potential for ameliorating the frailty condition in middle-aged and older people.

Therefore, the management of frailty should emphasize not only treatment, but also strengthen prevention and control. Early identification and implementation of accurate frailty management, based on the characteristics of different groups, are crucial for preventing frailty onset and mitigating its severity. This study identified several risk factors for frailty development, including female, aged ≥60 years, disability, obesity, short sleep duration, lack of social activity, rural residence, mid-western region, illiteracy, previously employed, and low-income. Living alone was found to significantly increases the risk of middle-aged and older people transitioning to the "C1 Rapid increase" group. Conversely, aged 45-59 years, normal BMI, eastern region, being working and having a more satisfying life were protective factors for the "C2: Slow decline" group. It can be seen that the developmental trajectory of frailty among the middle-aged and older people is jointly influenced by personal traits, behavioral feature, networking and other levels.

4.1. Personal traits layer

Males are more likely to maintain a stable low level of frailty index compared to females. Several studies have confirmed that the incidence of frailty in females is significantly higher than in males [17,20]. Post-menopausal hormonal changes in middle-aged and older females make them more susceptible to chronic diseases such as obesity and hypertension, often accompanied by depression and cognitive decline [9,21,22]. Individuals aged 45-59 years are more likely to maintain stable health and achieve improvements in frailty, whereas those aged 60 years and older exhibit a higher incidence of frailty and are more prone to rapid exacerbation. Frailty is exacerbated by age-related degenerative changes in organs, reduced physiologic reserve capacity, and decreased adaptive capacity to stress. Multiple studies have indicated a sharp increase in the incidence of frailty after the age of 60 [5,17]. The disability may not only limit their physical functioning and mobility, but may also induce psychological problems such as depression and anxiety, so leading to accelerated frailty. Individuals with a normal BMI are more likely to maintain stable health and mitigate frailty, whereas obesity exacerbates frailty, possibly due to muscle loss and decreased mobility associated with obesity [19,23], as well as an increased risk of chronic diseases. Balanced diets and moderate exercise should be consistently promoted to maintain a normal BMI, thereby promoting overall health and reducing the incidence of frailty.

4.2. Behavioral feature layer

People with normal or longer sleep durations are more likely to maintain stable health status than those with insufficient nighttime sleep durations. Nocturnal sleep deprivation aggravates debility, consistent with the results of a systematic review [24]. Adequate sleep promotes physical recovery and psychological well-being; while a study has noted a positive correlation between too much sleep and debility [25], this study shows a protective effect of normal or longer sleep duration. This suggests a complex correlation between sleep duration and debility. Therefore, further research on the relationship needs to focus on sleep quality. Adequate and high-quality sleep is essential in

middle-aged and older people, and there is a need to be vigilant about the potential risk of abnormal sleep duration for frailty. The effect of alcohol consumption on the development of debility is more complex, with non-drinkers more likely to be categorized as C2 group and C3 group, whereas drinkers are more likely to be categorized in the C4 group to maintain stable health status. Although alcohol consumption is often seen as a risk factor for debilitation [6,15], a study has pointed to a higher incidence of frailty in those who never drink and those who drink excessively [12], whereas moderate alcohol consumption is thought to reduce the risk of cardiovascular disease and contribute to reducing anxiety and depression [26]. The fact that some of the non-drinkers in this study achieved remission of frailty does not exclude the fact that some of them had to choose not to consume alcohol due to certain health problems, which would make it easier to be included in C3 group. People with higher life satisfaction are more likely to maintain stable health status and achieve frailty remission. This group has superior physical health, health behaviors and psychosocial status, including lower risk of pain and chronic disease, higher self-rated health and a more positive emotional state [27], which enables more actively manage disease, contribute to overall health, and in turn enhance the ability to cope with and alleviate frailty.

4.3. Networking layer

Non-participation in social activities is linked to higher frailty levels among middle-aged and older adults, likely due to its negative impact on mental health, cognition, and increased risk of falls and disability [22]. Additionally, middle-aged and older people in rural and central-western regions are at a heightened risk of frailty, consistent with the findings of Yin J's study [17]. This may be attributed to the deficiencies in economic development, healthcare accessibility, and social support in rural and central-western regions compared to urban and eastern areas. Living alone is another risk factor, consistent with Ren Q's findings [28]. However, Grden et al. found older adults living with family, possibly due to overdependence [29], while others reported lower frailty among those living alone due to greater self-sufficiency [30]. This study shows that middle-aged and elderly people living alone have a higher risk of rapid deterioration of frailty, which may be associated with the distinctive family socio-cultural context in China. The absence of family support and emotional comfort may exacerbate loneliness and psychological stress, while delayed health problem detection and healthcare access could further contribute to frailty susceptibility or exacerbation. To mitigate this, targeted support—such as regular visits and promoting social engagement—is essential for those living alone.

4.4. Living and working conditions layer

Frailty conditions are more severe in those who have previously worked than in those who are working. This may be closely related to changes in economic status after retirement, lifestyle changes, reduced physical activity and socialisation, and changes in psychological status [6,31]. Middle-aged and older people with lower literacy levels often lack the necessary knowledge of diseases and health protection due to cognitive deficits and limited access to information, which is also considered a risk factor for frailty, consistent with previous studies [5,28]. Low-income populations have difficulty accessing quality of life and healthcare services due to their economic status, which in turn increases the risk of frailty, consistent with existing research findings [28]. When conducting health interventions, health education resources that are appropriate for different educational backgrounds and economic levels should be developed and promoted to convey key health messages in a concise and easy-to-understand manner. Meanwhile, the active participation of family members and social support networks is encouraged to help middle-aged and elderly people better understand and apply health knowledge.

4.5. Policy environment layer

Although this study did not directly reveal the impact of health insurance and pension insurance on the frailty development trajectory of middle-aged and older people within the policy environment layer. It is plausible that these insurances indirectly influence the health status and frailty trajectory of this demographic by facilitating healthcare access [32,33], offering economic security, and boosting subjective well-being.

5. Conclusion

To summarize, this study has revealed the heterogeneity of the developmental trajectories of frailty in middle-aged and older people, identifying four potential categories, which is conducive to a more accurate understanding of the developmental process and individual differences in frailty. Based on the HEM model, the analysis found that the developmental trajectory of frailty in middle-aged and older people is collectively influenced by multi-level and multi-dimensional factors. And there are specific influencing factors among different trajectories, which can help the prediction of developmental trajectories and the identification of key populations. Therefore, the port of frailty prevention can be moved forward, and the starting point of screening age for key populations can be appropriately advanced to around 45 years old. In addition, the development of prevention and intervention measures should be formulated with attention to the developmental characteristics of different groups, focusing on heterogeneity in terms of gender, age, body mass index, literacy, number of family members, work status and so on. At the same time, targeted management should be implemented from multiple dimensions in conjunction with health ecology thinking to enhance the relevance and effectiveness of the measures, thereby effectively preventing or delaying the deterioration of frailty.

There are some limitations in this study. Although the HEM dimension provides a comprehensive framework, the analysis did not fully account for the impact of the policy environment on frailty trajectories. Furthermore, the specific effects of different types of health insurance and pension insurance on frailty development could be investigated in future research.

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Appendix

Table A1: Selection and assignment of variables based on the HEM.

Variable	Variable assignment	Variable	Variable assignment
Personal trait layer		Networking layer	
Gender	Male=1	Social activity	No=0

	Female=2		Yes=1
Age(years)	45-59 =1	Marital status	Married=1
	60 =2		Unmarried/Divorced/Widowed=2
Disability	No=0	Number of family members	3=1
	Yes=1		2=2
Body Mass Index	Underweight (18.5) =1		1=3
	Overweight (24.0-28.0) =2	Place of residence	Countryside=1
	Obese (28.0) =3		City=2
	Normal (18.5~24.0) =4	Region of residence	West=1
Behavioral feature layer			Central=2
Smoking	No=0		East=3
	Yes=1	Living and working conditions layer	
Alcohol consumption	No=0	Employment status	Previous=1
	Yes=1		Never=2
Physical activity	Low-intensity=1		Working=3
	Moderate-intensity=2	Highest level of education	Junior high school and above=1
	High-intensity=3		Elementary school=2
Night's sleep time(h)	5-9=1		Uneducated=3
	9=2	Annual per capita income (CNY)	High (10,000) =1
	5=3		Moderate (5,000~10,000) =2
Nap duration(h)	≤1=1		Low (5,000) =3
	1=2	Policy environment layer	
	No daytime napping=3	Pension insurance	No=0
Life satisfaction	Dissatisfied=1		Yes=1
	Satisfied=2	Health insurance	No=0
			Yes=1

Table A2: Logistic regression analysis for factors associated with frailty trajectory (Ref: C3).

Variable	C1vsC3		C2vsC3	
	β	OR (95%CI)	β	OR (95%CI)
Age (Ref: ≥60)				
45-59	0.16	1.22(0.98-1.53)	0.29	1.34(1.08-1.66) **
Disability (Ref: Yes)				
No	0.82	2.27(1.83-2.81) ***	0.02	0.78(0.84-1.27)
BMI (Ref: Normal)				
Overweight	-0.08	092(0.74-1.15)	-0.34	0.71 (0.56-0.90) **
Obese	-0.31	0.74(0.57-0.95) **	-0.55	0.58(0.44-0.77) ***
Night's sleep time (Ref:<5h)				
5-9h	0.56	1.75(1.40-2.17) ***	-0.09	0.92(0.74-1.14)
Life satisfaction (Ref: Satisfied)				
Dissatisfied	-0.84	0.43(0.34-0.54) ***	-0.26	0.77(0.62-0.96) *
Number of family members (Ref: 1)				
2	-0.46	0.64(0.43-0.94) *	-0.17	0.85(0.54-1.32)
Region of residence (Ref: East)				
West	-0.36	0.70(0.55-0.89) **	-0.20	0.82(0.64-1.05)
Central	-0.36	0.70(0.56-0.88) **	-0.43	0.65(0.50-0.84) ***
Employment status (Ref: Working)				
Previous	-0.56	0.57(0.46-0.70) ***	-0.30	0.75(0.60-0.93) **
Annual per capita income (Ref: Low)				
High	0.46	1.58(1.22-2.04) ***	0.02	1.02(0.76-1.36)
Moderate	0.30	1.35(1.05-1.73) *	0.07	1.08(0.82-1.42)

Standard errors in parentheses: * p<0.05, ** p<0.01, *** p<0.001