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Identification and prediction of frailty among community-dwelling older Japanese adults based on Bayesian network analysis: a cross-sectional and longitudinal study

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Abstract

Background Frailty is a multifactorial syndrome; through this study, we aimed to investigate the physiological, psychological, and social factors associated with frailty and frailty worsening in community-dwelling older adults.

Methods We conducted a cross-sectional and longitudinal study using data from the "Community Empowerment and Well-Being and Healthy Long-term Care: Evidence from a Cohort Study (CEC)," which focuses on community dwellers aged 65 and above in Japan. The sample of the cross-sectional study was drawn from a CEC study conducted in 2014 with a total of 673 participants. After excluding those who were frail during the baseline assessment (2014) and at the 3-year follow-up (2017), the study included 373 participants. Frailty assessment was extracted from the Kihon Checklist, while social relationships were assessed using the Social Interaction Index (ISI). Variable selection was performed using Least Absolute Shrinkage and Selection Operator (LASSO) regression and their predictive abilities were tested. Factors associated with frailty status and worsening were identified through the Maximum-min Hillclimb algorithm applied to Bayesian networks (BNs).

Results At baseline, 14.1% (95 out of 673) participants were frail, and 24.1% (90 out of 373) participants experienced frailty worsening at the 3-years follow up. LASSO regression identified key variables for frailty. For frailty identification (cross-sectional), the LASSO model's AUC was 0.943 (95%CI 0.913–0.974), indicating good discrimination, with Hosmer–Lemeshow (H–L) test $p=0.395$. For frailty worsening (longitudinal), the LASSO model's AUC was 0.722 (95%CI 0.656–0.788), indicating moderate discrimination, with H–L test $p=0.26$. The BNs found that age, multimorbidity, function status, and social relationships were parent nodes directly related to frailty. It revealed an 85% probability of frailty in individuals aged 75 or older with physical dysfunction, polypharmacy, and low ISI scores; however, if their social relationships and polypharmacy status improve, the probability reduces to 50.0%. In the longitudinal-level frailty worsening model, a 75% probability of frailty worsening in individuals aged 75 or older with declined physical function and ISI scores was noted; however, if physical function and ISI improve, the probability decreases to 25.0%.

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Conclusion Frailty and its progression are prevalent among community-dwelling older adults and are influenced by various factors, including age, physical function, and social relationships. BNs facilitate the identification of interrelationships among these variables, quantify the influence of key factors. However, further research is required to validate the proposed model.

Keywords Frailty, Social relationships, Bayesian analysis, LASSO regression, Prediction model

Background

Frailty is a common condition among older adults, characterized by the decline of multiple systems including physical, social, and cognitive functions [1, 2]. In Japan, the prevalence of frailty among community-dwelling older adults ranges from 8 to 17% and is expected to increase as the population ages [3–6]. Several factors contribute to an increased risk of developing frailty, including ageing, low physical activity, polypharmacy, multimorbidity, and insufficient social support [7–9]. Frailty reduces an individual's ability to cope with external stressors [10, 11], making them more vulnerable to adverse health outcomes such as falls, hospitalization, increased disability, and higher mortality rates [12–15].

Evidence suggests that frailty is dynamic and may progress from robustness to functional decline [16, 17]. Studies from different countries have reported varying rates of frailty progression. A previous study [18] found that 23.7% older adults showed deterioration in frailty status after a year in a Chinese sample. Robust older adults have a 4%–7% chance of developing frailty each year In Korea sample [19]. Another study reviewed [20] 16 studies with an average follow-up of 3.9 years and found that 29.1% of participants experienced frailty worsening. Moreover, for every 0.01 increase in frailty score, the risk of death increased by 5% [21], with rapidly progressing individuals facing a higher risk of adverse outcomes [22]. Compared to physical measures used in these studies, the multidimensional measurement is commonly used to measure frailty in Japan [23–26], including physical function, nutritional status, oral health, housebound status, and cognitive function and provide a more comprehensive assessment of frailty.

Frailty is a complex condition resulting from multiple interconnected factors. Traditional statistical models typically show relationships between dependent and independent variables but fail to capture comprehensive impacts [27]. Bayesian networks (BNs), a graphical statistical tool, can display probabilistic relationships between variables through a directed acyclic graph (DAG) [28, 29]. To enhance the construction of BNs, we use Least Absolute Shrinkage and Selection Operator (LASSO) regression, a method that helps select relevant features and reduce the number of variables [30]. These methods are particularly well-suited for studying frailty, as they can capture the complex, interconnected nature of multiple factors contributing to this syndrome.

The current study applies Bayesian networks with LASSO regression at both cross-sectional and longitudinal levels and aimed to provide insights that can inform preventive interventions and therapeutic approaches for community-dwelling older adults.

Methods

Design and participants

This study used a mixed design that permitted both cross-sectional and longitudinal analyses. Participants were recruited from the "Community Empowerment and Care for Well-being and Healthy Longevity: Evidence from a Cohort Study (CEC)" that started in 1991 and was conducted every 3 years among all residents living in the suburban of central Japan to examine factors related to well-being and longevity. This study used data from the 2014 and 2017 waves.

The inclusion criterion was community-dwelling older adults aged 65 years and over. A total of 1004 participants from the 2014 sample responded to the baseline survey. Of them, 673 participants were included in the cross-sectional study analysis after excluding 331 participants with missing frailty data. In the longitudinal study, we excluded 95 participants with frailty at baseline, 52 who were lost to follow-up after 3 years of follow-up, and 153 with missing frailty data, 373 participants were included in the analysis.

Frailty status assessment

We assessed participants' frailty using 1–20 items from the Kihon Checklist (KCL), which is widely used in Japan to screen for frailty in older adults [23, 24] and has been shown to have better predictive ability for adverse outcomes than the total 25-item version [25, 26]. It includes physical strength, nutritional status, oral function, housebound status, and cognitive function domains. A score of 7 or more out of 20 was defined as frailty (sensitivity: 77.0%; specificity: 75.6%) [25], and we defined frailty worsening as non-frailty developing to frailty.

Socio-demographic characteristics

Socio-demographic characteristics included age (65–74 years; 75 years or older), sex (male and female), living

status (alone; together), and subjective economic status (poor; better off).

Lifestyle characteristics

In terms of lifestyle behaviors, the questionnaire assessed participants' smoking habits (non-smoker, current smoker, and ex-smoker), heavy alcohol intake (daily and non-daily drinking), and physical activity (inactive and active). The dietary diversity score was calculated based on the sum of frequencies of each food item. The seven types of food included: vegetables, fruits, meat, fish, eggs, beans, and dairy products. The frequency of eating was defined as: 1, hardly eating; 2, 1–2 times per week; 3, 3–4 times per week; and 4, daily. The total dietary diversity scores ranged 7–28.

Disease characteristics

Self-reported medical history data on having diagnosed comorbidities (hypertension, heart disease, hyperlipidemia, diabetes, respiratory disease, liver-stomach disease, kidney disease, musculoskeletal disorders, blood and immune system disorders, cancer, dementia, stroke, and Parkinson's disease) were recorded. Multimorbidity was defined as having two or more chronic diseases, and participants who had taken five or more drugs were considered to have polypharmacy.

Physical condition

According to Verbrugge and Jette's model, decreased functional status is a disability-related process that can be defined as difficulty performing activities of daily living [31]. We defined people who needed help or care daily as lacking functional status [32]. Function status was assessed using the item, "Do you need some help or care in your daily life?" If the answer was "yes," then the participant experienced physical dysfunction. After 3 years of follow-up, if the answer changed from not needing help to needing help, the participant's functional status was said to have declined.

Psychological condition

The risk of depression in the participants was assessed using items 20–25 of the KCL; scores of 2 or higher were indicative of a depressed mood. Life satisfaction was assessed using one item: "Are you satisfied with your present life?" (yes or no). When participants' answers changed from yes to no after the follow-up, life satisfaction was said to have declined.

Social relationships

Social relationships were measured using the Social Interaction Index (ISI) [33], which evaluates different aspects of social relationships and includes a total of 18 items and five subscales, including social curiosity, independence, interaction, participation, and feeling safe [34]. The scale ranges from 0 to 18, with higher scores indicating stronger social relationships and has been proven to be valid and reliable [35].

Statistical analysis

Qualitative data are presented as numbers (n) and percentages (%). The chi-square and Fisher's exact tests were used for inter-group comparisons. Data complying with normal distribution were described by mean ± standard deviation (SD). For quantitative data that did not conform to a normal distribution, the medians ± 25th–75th percentiles were used to describe the data, and the rank-sum test was used for inter-group comparisons. Without special instructions, the test level α was set at 0.05. Missing values in less than 20% of the covariates were imputed using values from five datasets created with random forests for multivariate imputation, with the parameters set as follows: number of imputations (m) = 5, maximum number of iterations (maxit) = 50, method (meth) = 'rf' (random forest), and random seed (seed) = 1220. The optimal imputed values were determined based on the density plot distribution comparison between the original and imputed data.

Factors associated with cross-sectional frailty and longitudinal frailty worsening were selected using LASSO regression. The optimal tuning parameter (λ) was identified through a tenfold cross-validation. Selected factors were then included in multivariate logistic regression. Model performance was evaluated using the area under the receiver operating characteristic (ROC) curve (AUC) for discrimination and calibration plots with Hosmer–Lemeshow goodness-of-fit test for calibration. LASSO regression was used to address multicollinearity [36]. It incorporates a penalty term to minimize estimated parameters, setting coefficients below a threshold to zero. This method identifies variables with stronger impacts on the dependent variable [30].

BN analysis was employed to examine interactions and probability dependencies between variables [37]. The maximum min hill climb algorithm was used for structural learning, creating the network topology [38]. Parameter learning used maximum likelihood estimation to estimate conditional probabilities for each node [39]. The study flowchart is shown in Fig. 1.

In addition, we conducted sensitivity analysis to identify key variables of frailty identification and worsening. Our analysis focused on the 'frailty' and 'frailty worsening' node as the target variable. Analyses were performed using R version 4.2 (packages: "glmnet" for LASSO regression, "mice" for imputation), GeNIe 2.3 for BNs sensitivity analysis.

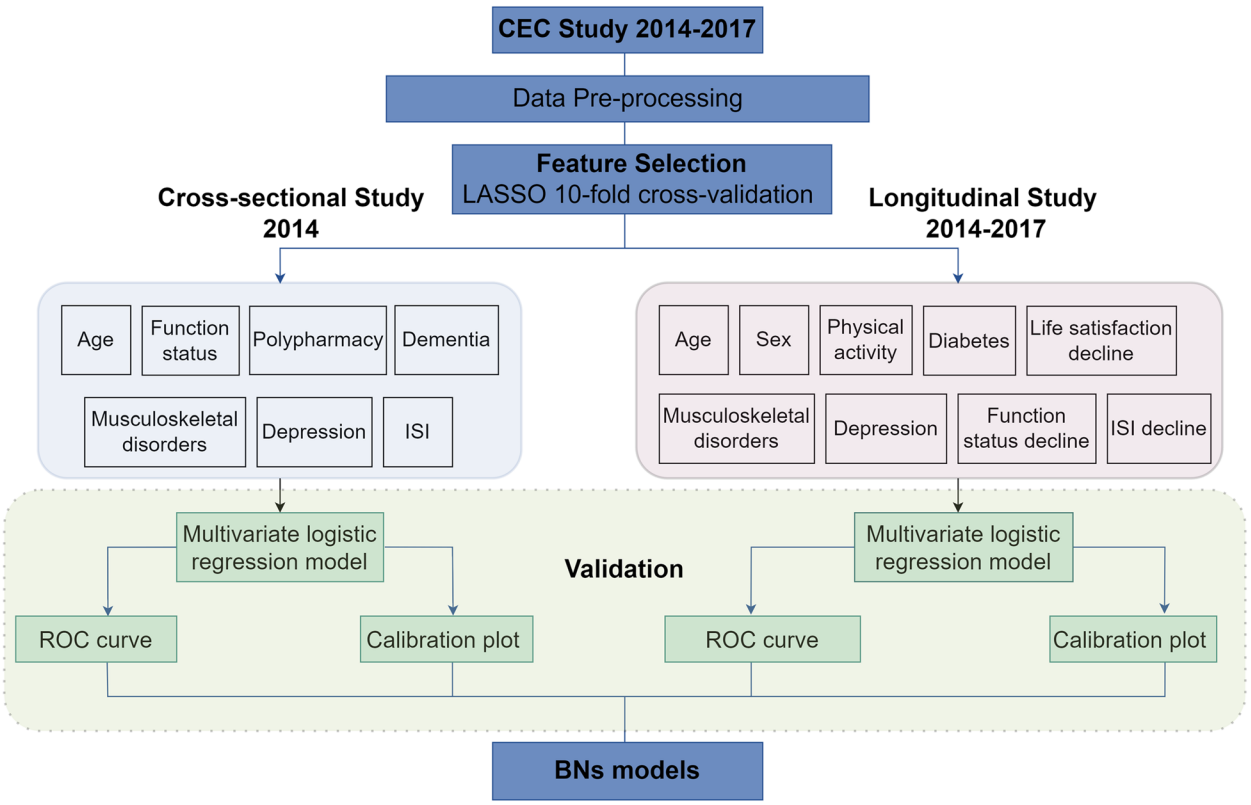

Fig. 1 Flowchart of the core steps of the study

Results

A total of 673 participants (age: 73.65 ± 7.10 years, female 49.7%) were included at baseline. Of these, 14.1% individuals were classified as frail. After 3 years, 373 participants completed the follow-up, and 24.1% individuals experienced frailty worsening. Table 1 presents the characteristics of the participants. At the cross-sectional level, older adults who were older, female, daily drinkers, and physically inactive were more likely to fail; furthermore, they had lower dietary diversity, functional status, social relationships, and life satisfaction, and higher proportions of multimorbidity, polypharmacy, stroke, heart disease, dementia, musculoskeletal disorders, and depression.

Table 2 shows the participants' characteristics according to frailty worsening. The proportion of individuals aged 75 years or older, with diabetes, musculoskeletal disorders, and depression in people with frailty worsening was higher. Furthermore, the functional status, life satisfaction, and social relationships of these people were significantly decreased ($p < 0.05$).

At baseline, 673 participants were screened using LASSO regression and tenfold cross-validation, and seven variables that were significantly correlated with frailty were screened in Fig. 2A and B. The horizontal axis represents the logarithm of the λ, and the vertical axis represents the model error, with each curve corresponding to a variable. It shows status changes, the coefficient relative to the coefficient vector of the path of the ℓ 1 norm. The best λ is the lowest point of the red curve and the number of variables is 15. The dotted line on the right represents a clean model (seven variables) within 1 SE. Since the model corresponding to the λ.min and λ.1SE has little variation in error, we choose optimal when λ was log(x) = -3.39 as it maintains a low model error while including fewer variables. And then, we further incorporate these potential factors related to frailty into the multivariate logistic regression model. Ultimately, being 75 years or older (odds ratio [OR] 1.93, 95% confidence interval [CI] 0.97–3.84), having physical dysfunction (OR 19.04, 95%CI 7.86–46.16), polypharmacy (OR 3.04, 95%CI 1.47–6.27), dementia (OR 25.54, 95%CI 2.22–293.81), musculoskeletal disorders (OR 5.07, 95%CI 2.23–11.52), depression (OR 4.93, 95%CI 2.46–9.90), and social relationships (OR 0.71, 95%CI 0.62–0.81) were associated with frailty among older adults (Supplementary Table 1). The model's AUC value was 0.943 (95%CI 0.913–0.974), and the H–L test $p = 0.395$, indicating good fit (see Supplementary Fig. A and B curve and calibration plot).

Table 1 Participants characteristics (*N* = 673)

Variables	Frailty status			
	Non-frailty (*N* = 578)	Frailty (*N* = 95)	χ^2/t	*P*
General characteristics				
Age (years, N, %)			51.25	< 0.001
65–74	382 (66.1)	26 (27.4)		
≥ 75	196 (33.9)	69 (72.6)		
Female (N, %)	287 (49.7)	65 (68.4)	11.52	< 0.001
Living alone (N, %)	25 (4.3)	4 (4.2)	-	1.000*
Subjective economic status (Poor, N, %)	317 (54.8)	54 (56.8)	0.13	0.717
Lifestyle characteristics				
Daily drinking (N, %)	128 (22.2)	6 (6.3)	12.82	< 0.001
Current smoker (N, %)	67 (11.6)	7 (7.4)	5.72	0.057
Physically active (N, %)	376 (65.1)	25 (26.3)	50.84	< 0.001
Diet diversity score (median, IQR)	21.00 (18.00, 23.00)	19.00 (15.00, 22.00)	-3.41	< 0.001#
Physical characteristics				
Function status (dysfunction, N, %)	16 (2.8)	55 (57.9)	262.74	< 0.001
Disease characteristics				
Multimorbidity (N, %)	152 (26.3)	48 (50.5)	22.93	< 0.001
Polypharmacy (N, %)	85 (14.7)	44 (46.3)	52.62	< 0.001
Hypertension (N, %)	262 (45.3)	49 (51.6)	1.28	0.257
Diabetes (N, %)	72 (12.5)	16 (16.8)	1.38	0.240
Respiratory disease (N, %)	22 (3.8)	8 (8.4)	-	0.057*
Stoke (N, %)	12 (2.1)	13 (13.7)	-	< 0.001*
Hyperlipemia (N, %)	48 (8.3)	7 (7.4)	0.10	0.758
Cancer (N, %)	14 (2.4)	1 (1.1)	-	0.708*
Heart disease (N, %)	46 (8.0)	17 (17.9)	9.49	0.002
Liver-stomach disease (N, %)	38 (6.6)	4 (4.2)	0.78	0.377
Kidney disease (N, %)	30 (5.2)	3 (3.2)	-	0.607*
Musculoskeletal disorder (N, %)	39 (6.8)	23 (24.2)	29.75	< 0.001
Dementia (N, %)	1 (0.2)	16 (16.8)	-	< 0.001*
Blood and immune system disorder (N, %)	8 (1.4)	3 (3.2)	-	0.194*
Parkinson (N, %)	1 (0.2)	2 (2.1)	-	0.054*
Psychologic characteristics				
Depression (N, %)	88 (15.2)	58 (61.1)	100.87	< 0.001
Life dissatisfaction (N, %)	60 (10.4)	31 (32.6)	34.55	< 0.001
Social relationships				
ISI score (median, IQR)	17.00 (16.00, 18.00)	14.00 (10.00, 15.00)	-11.11	< 0.001#
Social curiosity (median, IQR)	5.00 (4.00, 5.00)	2.00 (1.00, 4.00)	-9.52	< 0.001#
Independence (median, IQR)	4.00 (4.00, 4.00)	4.0 (3.00, 4.00)	-8.93	< 0.001#
Interaction (median, IQR)	3.00 (3.00, 3.00)	3.0 (2.00, 3.00)	-6.84	< 0.001#
Participation (median, IQR)	4.00 (3.00, 4.00)	1.00 (1.00, 3.00)	-9.97	< 0.001#
Telling of safety (median, IQR)	2.00 (2.00, 2.00)	2.00 (2.00, 2.00)	-3.76	< 0.001#

ISI Index of Social Interaction, *IQR* Interquartile range

* Fisher's exact test

rank-sum test

The results of LASSO regression with 10-fold cross-validation for frailty worsening is shown in Fig. 2C and D. To achieve the highest predictive accuracy and more important variables, we selected λ.min, where log(λ) = -3.61. The final predictive model (Supplementary Table 2) included being 75 years or older (OR 2.05, 95%CI

Table 2 Participants characteristics by the transition of frailty ($N=373$)

Variables	Frailty status			
	Non-worsening ($N=283$)	Worsening ($N=90$)	χ^2/t	*P*
General characteristics				
Age (years, N, %)				
65–74	219 (77.4)	55 (61.1)	9.28	0.002
≥ 75	64 (22.6)	35 (38.9)		
Female (N, %)	134 (47.4)	48 (53.3)	0.98	0.323
Living alone (N, %)	14 (5.0)	3 (3.3)	-	0.772*
Subjective economic status (Poor, N, %)	146 (51.6)	54 (60.0)	1.94	0.163
Lifestyle characteristics				
Daily drinking (N, %)	70 (24.7)	16 (17.8)	1.86	0.172
Current smoker (N, %)	37 (13.1)	9 (10.0)	0.60	0.742
Physically active (N, %)	200 (70.7)	55 (61.1)	2.89	0.089
Diet diversity score decline (N, %)	111 (39.2)	30 (33.3)	1.01	0.316
Physical characteristics				
Function status decline (N, %)	10 (3.5)	21 (23.3)	35.13	< 0.001
Clinical characteristics				
Multimorbidity (N, %)	74 (26.2)	27 (30.0)	0.51	0.474
Polypharmacy (N, %)	37 (13.1)	16 (17.8)	1.24	0.266
Hypertension (N, %)	135 (47.7)	37 (41.1)	1.19	0.274
Diabetes (N, %)	27 (9.5)	17 (18.9)	5.74	0.017
Respiratory disease (N, %)	11 (3.9)	4 (4.4)	-	0.764*
Stoke (N, %)	5 (1.8)	1 (1.1)	-	1.000*
Hyperlipemia (N, %)	31 (11.0)	8 (8.9)	0.31	0.577
Cancer (N, %)	7 (2.5)	2 (2.2)	-	1.000*
Heart disease (N, %)	22 (7.8)	10 (11.1)	0.97	0.325
Liver-stomach disease (N, %)	17 (6.0)	7 (7.8)	0.36	0.551
Kidney disease (N, %)	12 (4.2)	5 (5.6)	-	0.570*
Musculoskeletal disorder (N, %)	16 (5.7)	11(12.2)	4.39	0.036
Dementia (N, %)	0 (0.0)	1(1.1)	-	0.241*
Blood and immune system disorder (N, %)	3 (1.1)	2 (2.2)	-	0.598*
Parkinson (N, %)	1 (0.4)	0 (0.0)	-	1.000*
Psychologic characteristics				
Depression (N, %)	30 (10.6)	20 (22.2)	7.94	0.005
Life dissatisfaction decline (N, %)	36 (12.7)	21 (23.3)	5.94	0.015
Social relationships				
ISI decline (N, %)	68 (24.0)	33 (36.7)	5.52	0.019

ISI Index of Social Interaction

* Fisher's exact test

1.17–3.58), female (OR 1.46, 95%CI 0.85–2.50), physically active (OR 0.74, 95%CI 0.43–1.28), having musculoskeletal disorders (OR 1.90, 95%CI 0.76–4.72), depression (OR 1.87, 95%CI 0.94–3.75), function status decline (OR 5.84, 95%CI 2.52–13.56), diabetes (OR 2.65, 95%CI 1.28–5.47), life satisfaction decline (OR 1.76, 95% CI 0.88–3.50), and ISI decline (OR 1.54, 95%CI 0.88–2.71). The model's AUC value was 0.722 (95%CI = 0.656–0.788), indicating moderate discrimination. The H–L test $p=0.26$, suggesting good model fit (Supplementary Figure C and D for ROC curve and calibration plot).

According to the variables identified by LASSO regression, we constructed two BNs models. The first model, focusing on frailty-related factors (Fig. 3A), consists of eight nodes and 16 directed edges. It shows that age, functional status, and ISI are directly related to frailty. Musculoskeletal disorders, dementia, polypharmacy and depression are indirectly link to frailty. The

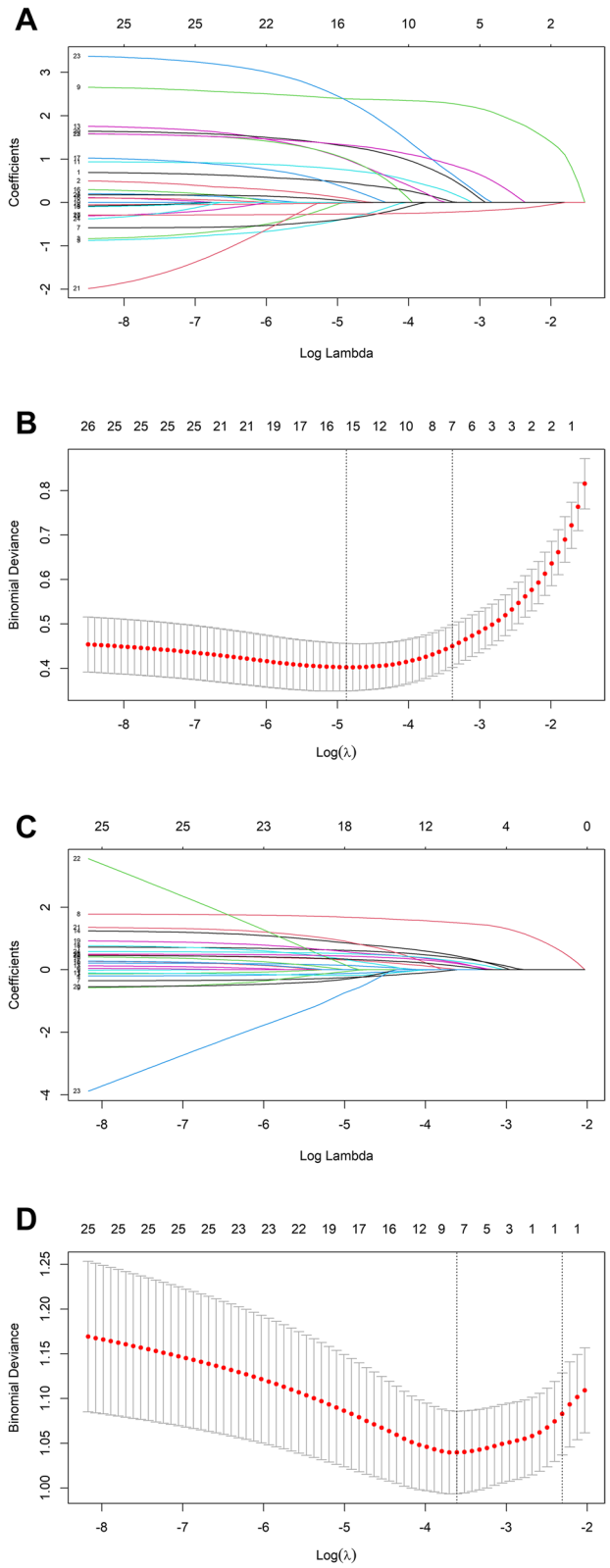

Fig. 2 Results of LASSO regression with tenfold cross-validation. **A**, **B** LASSO regression for frailty identification (cross-sectional study); **C**, **D** LASSO regression for frailty transition (longitudinal study). LASSO, least absolute shrinkage and selection operator

second model, predicting frailty progression (Fig. 3B) comprises 10 nodes and 22 directed edges. This model reveals that age, decline in functional status, and ISI scores are directly related to frailty worsening. Other factors such as sex, musculoskeletal disorders, diabetes, physical activity, and depression are indirectly linked to frailty worsening through a complex network relationship.

Figure 4 presents the conditional probability distribution of frailty and its progression, quantifying the relationship between parent nodes and the probability of frailty and worsening. Fig. 4A reveals an 85% probability of frailty in individuals aged 75 or older with physical dysfunction, polypharmacy, and low ISI scores. Conversely, participants aged 65–74 years with normal physical function and high ISI scores have the lowest conditional probability of frailty at 3.1%. Moreover, Fig. 4B shows an 83.3% probability of frailty worsening in individuals aged 75 or older with physical dysfunction, polypharmacy, and decreased ISI scores. In contrast, the lowest conditional probability of frailty worsening, at 16.1%, is observed in individuals aged 65–74 years with normal physical functioning and high ISI scores.

Based on the participant's physical, psychological, and social factors, BNs can infer the individual probability of frailty and its progression in community-dwelling older adults. For instance, a participant aged 75 years or older with polypharmacy, physical dysfunction, and low ISI scores has an estimated frailty probability of 85.0%. If their social relationships and polypharmacy status improve, this probability reduces to 50.0% (Fig. 5A and B). Similarly, the probability of frailty worsening is 75.0% for participants aged 75 years or older with reduced physical function and social relationship scores. However, if their physical function and social relationships improve, the probability decreases to 25.0% (Fig. 5C and D).

The results of BNs sensitivity analysis revealed the key factors influencing frailty identification and its worsening. For frailty identification, the top three influential variables were functional status, dementia, and age, with functional status having the greatest impact (sensitivity value: 0.57), followed by dementia (sensitivity value: 0.30) and age (sensitivity value: 0.10). Regarding frailty worsening, the most influential variables were functional status decline, age, and ISI decline. Functional status decline had the greatest effect (sensitivity value: 0.22), followed by age (sensitivity value: 0.15) and ISI decline (sensitivity

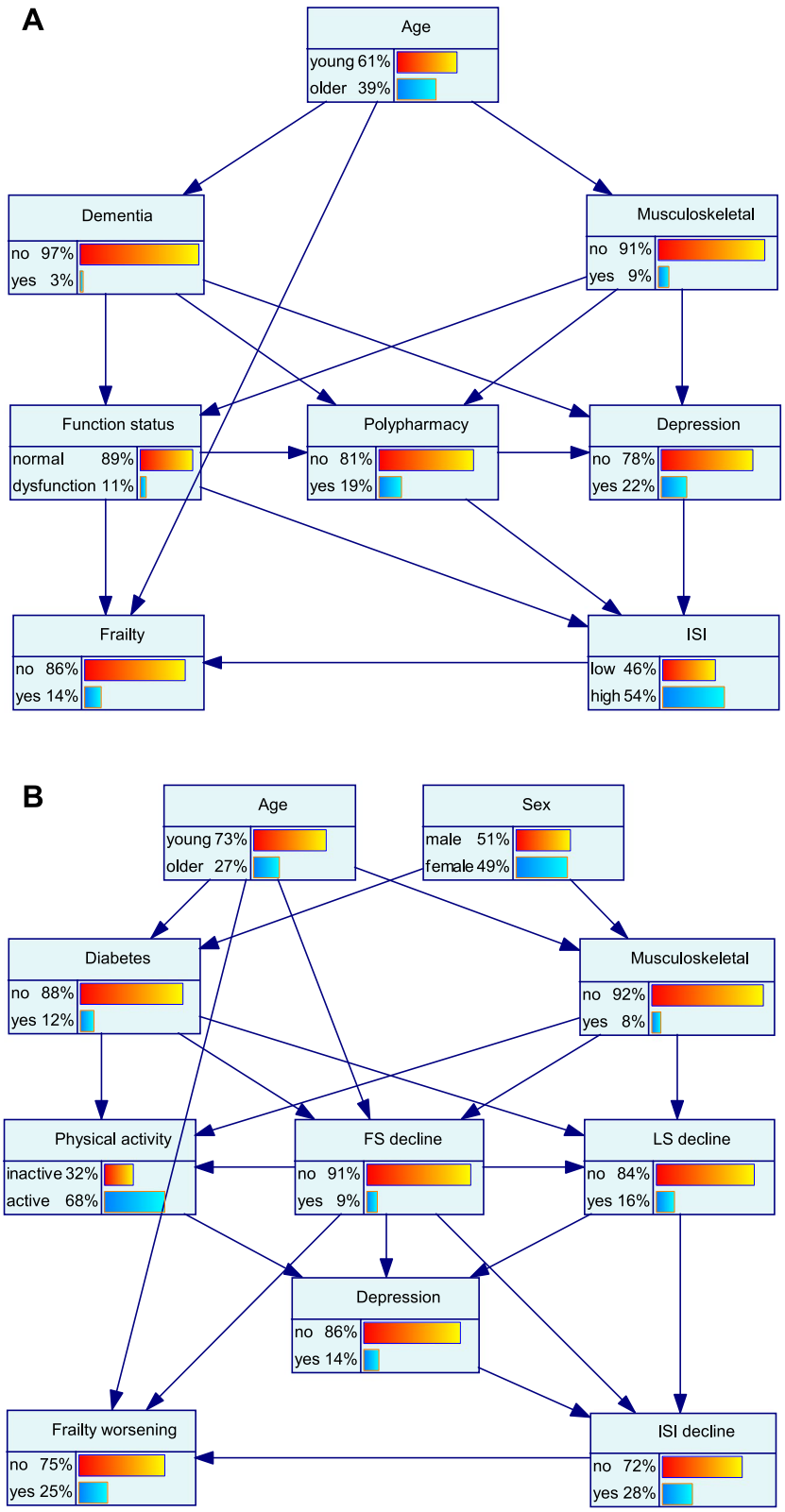

Fig. 3 BNs topology of factors relating to frailty and frailty worsening. **A** BNs topology of factors relating to frailty status; **B** BNs topology of predictors relating to frailty worsening. Young: 65–75 years, older: ≥ 75 years. FS: function status. ISI: Index of Social Interaction score; divided by median; low: ISI score < 17, high: ISI score ≥ 17. BNs, Bayesian networks; ISI, Index of Social Interaction

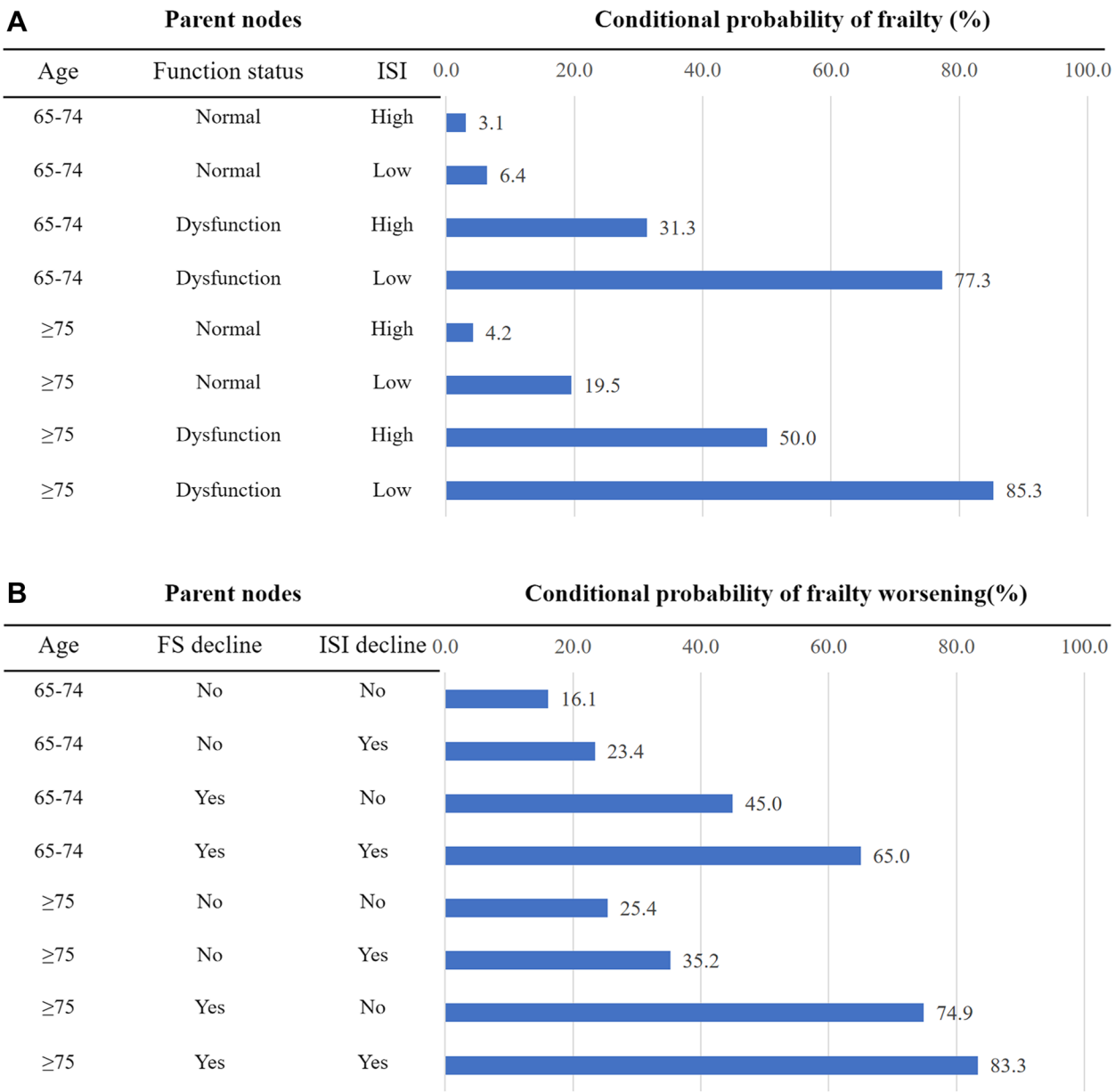

Fig. 4 Conditional probability distribution of frailty and frailty worsening. **A** Conditional probability distribution of frailty with age, function status, and ISI as parent nodes; **B** Conditional probability distribution of frailty worsening with age, decline of function status (FS) and ISI as parent nodes. FS, function status; ISI, Index of Social Interaction

value: 0.06). Additionally, musculoskeletal disorder and diabetes were also identified as significant factors.

Discussion

In the current study, we found that the prevalence of frailty among older adults in Japanese communities was assessed as 14.1%. Furthermore, at the longitudinal level, 24.1% of the participants transitioned from a non-frail to a frail state after 3 years. These results are comparable to previous findings [18–20] indicating that frailty and its progression are relatively common among community-dwelling older adults. Our study combined LASSO regression and BNs to offer a comprehensive analysis of these factors, providing valuable insights for future research.

Frailty is a multifaceted condition influenced by various factors. Our findings revealed that age, function status, and social relationships were directly related to frailty

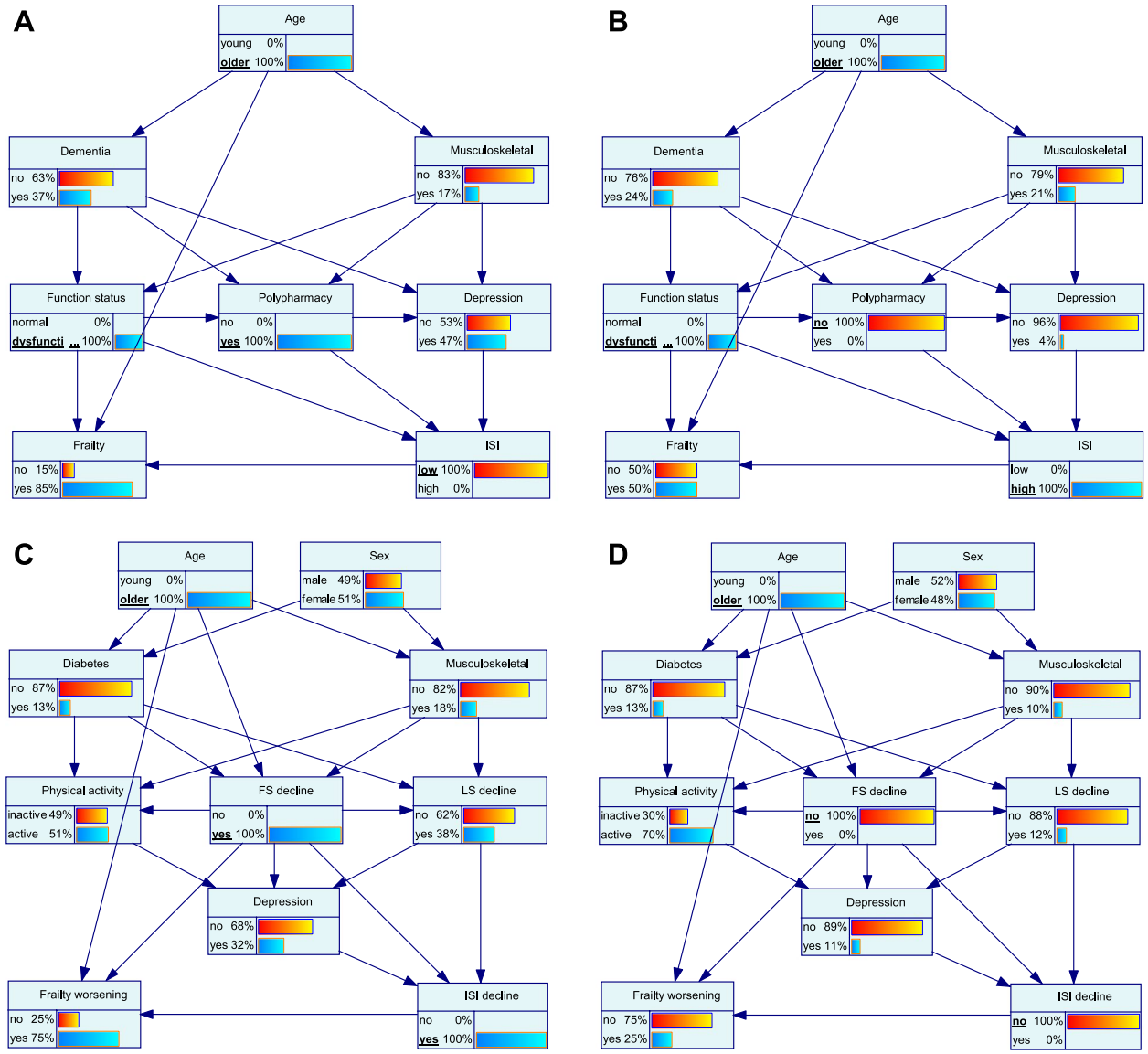

Fig. 5 BNs under known evidence variables. **A** Conditional probability distribution of frailty for individuals who are 75 years old or older, with physical dysfunction, polypharmacy, and low ISI scores; **B** Conditional probability distribution of frailty with age 75 or older, physical dysfunction, high ISI scores, and without polypharmacy. **C** Conditional probability distribution of frailty worsening with age 75 or older, with FS and ISI decline. **D** Conditional probability distribution of frailty worsening with age 75 or older, without FS and ISI decline. FS, function status; ISI, Index of Social Interaction

and frailty worsening. Age-related changes, particularly those affecting the musculoskeletal system, are common in older adults. Our study found that musculoskeletal disorders are associated with frailty through function status. The underlying mechanisms can be linked to factors identified in previous studies, such as decreased muscle mass and strength, reduced bone density, inflammation, immune dysfunction, and metabolic changes [40–43]. These physiological changes can contribute to musculoskeletal issues through alterations in muscle protein turnover, hormonal imbalances, and decreased physical activity [44]. Consequently, these changes may affect older adults' physical function and potentially contributing to frailty and its worsening [45].

Our study also highlighted the indirect role of social relationships and depression in frailty through their impact on function status. Evidence suggests significant interactions between social factors, mental health, and frailty [46]. Social relationships, assessed through the ISI, provide access to health-related information and social

support, which can buffer stress and promote healthy behaviors [47]. These mechanisms act as protective factors against frailty. Cohen et al. [48] suggested that social support influences health behaviors and functional states by reducing stress and encouraging positive health behaviors, thereby mitigating the risk of frailty and its progression.

Dementia, musculoskeletal disorders, polypharmacy, and depression were indirectly related to frailty by affecting physical function and social relationships. The relationship between dementia and frailty is particularly noteworthy as they often coexist and synergistically impact overall health in older adults [49]. Our logistic regression results showed a significant association between dementia and frailty, though with a wide confidence interval, indicating uncertainty likely due to the small number of dementia cases or significant differences between the frail and non-frail groups. Nevertheless, the BNs model developed supports this relationship, reinforcing the importance of considering dementia as a key factor in frailty assessments. Additionally, the results of the BNs indicate that reducing polypharmacy and improving social relationships among individuals aged 75 years or older can lower frailty risk. Our BNs model suggests that polypharmacy, defined as taking five or more medications, is associated with frailty indirectly through depression and social relationships. Previous studies have validated the mechanisms behind this association, showing that certain medications, such as tranquilizers, anticholinergics, and corticosteroids, can cause psychological side effects leading to depressive symptoms [50–55]. These symptoms can reduce social interactions, thereby increasing frailty risk [52, 53].

Our BNs model suggests that age, function status decline, and ISI decline are directly associated with frailty worsening. In contrast, sex, diabetes, musculoskeletal disorders, physical activity, depression, and decline in life satisfaction do not show direct associations with frailty worsening but may be indirectly associated through their relationships with other factors in the model. Among these, the most significant impacts were from the function status decline, age, ISI decline, musculoskeletal disorders, and diabetes. Our study indicated that the relationship between diabetes and worsening frailty is associated with decreased physical activity and functional status. This connection may be due to complications in patients with diabetes, such as peripheral neuropathy (nerve damage) and peripheral arterial disease (reduced blood flow to the extremities) [56, 57], which further impair their physical capabilities and functional status. While life satisfaction reflects an individual's overall contentment with life, and chronic diseases or declining physical function can decrease life satisfaction, leading to depression and reduced social relationships, thereby increasing the risk of frailty. Conversely, individuals with high life satisfaction typically have stronger social networks and support systems [58]. These social relationships can provide emotional and practical support, promote engagement in healthy behaviors (e.g., physical activity and healthy diet), and help individuals cope with the aging and frailty challenges [59].

Our study's BNs model can predict the probability of frailty and its progression, helping to identify individuals at risk and prioritize interventions. This study had several strengths. First, frailty occurrence is complex and involves several factors. We combined LASSO regression with BNs to identify and predict frailty status in community-dwelling older Japanese adults. LASSO effectively handles high-dimensional data and multiple variables while avoiding overfitting [60, 61]. BNs characterize interactions between factors and their effects on frailty through DAG [28, 29]. Second, rather than using a single measure of social participation, we used the ISI to comprehensively assess various daily social activities that may influence frailty.

Limitations

Our study has some limitations. First, we used a common frailty screening tool in Japan and data from a Japanese community in a population-based study. The results may vary when different assessment tools are used. Second, we did not collect information on income and education, which may influence frailty. Future studies should include these variables. Third, we relied on self-reported data, which may not accurately reflect actual physical capabilities. Future studies could incorporate objective measures like walking speed and grip strength. Fourth, a critical limitation is the lack of external validation. While we performed cross-validation of the LASSO model and sensitivity analysis on the BNs, we did not validate our findings in an independent cohort. Future research should prioritize external validation, k-fold cross-validation, and comparison with larger, external cohorts to enhance the model's accuracy and generalizability. Finally, with a larger sample size, more detailed stratification of frailty factors could lead to a more robust model.

Conclusions

This study revealed the prevalence of frailty and its progression among Japanese community-dwelling older adults while examining the variations in the conditional probability of experiencing frailty and its worsening based on physical, psychological, and social factors. Our findings indicated a direct association between age, function status, and social relationships in older adults with frailty and its worsening. Moreover, our

study highlights the potential benefits of the early identification of factors contributing to functional decline and social relationships decline, as it can aid in the prevention and delay of frailty development. BNs facilitate a deeper comprehension of the intricate interdependencies among variables, necessitating further investigation to consistently validate and optimize this framework for the early detection of risk factors and enhanced preventive interventions for frailty.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
YMJ and LY contributed to the conception, design, analysis, drafting and revision of this paper. KM, MM, JDD, CMY, ZJR, QML, and HLJ contributed to the interpretation, drafting and revision of this paper. KM, MM, JDD, ZZ, and LX contributed to the collection of the data. TA was the primary researcher of the original data. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee of the University of Tsukuba (approval number 1331–5). The research utilized anonymized data provided by the local government. According to the Ethical Guidelines for Medical and Health Research Involving Human Subjects in Japan, the requirement for written informed consent was waived. Participants retained the right to opt out of the study for any reason. All procedures were conducted in accordance with the principles of the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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