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Trends, trajectories and predictors of healthy aging

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Trends, trajectories and predictors of healthy aging

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Deep-learning model for predicting physical fitness in possible sarcopenia: analysis of the Korean physical fitness award from 2010 to 2023

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Introduction: Physical fitness is regarded as a significant indicator of sarcopenia. This study aimed to develop and evaluate a deep-learning model for predicting the decline in physical fitness due to sarcopenia in individuals with potential sarcopenia.

Methods: This study used the 2010–2023 Korean National Physical Fitness Award data. The data comprised exercise- and health-related measurements in Koreans aged >65 years and included body composition and physical fitness variables. Appendicular muscle mass (ASM) was calculated as ASM/height^2 to define normal and possible sarcopenia. The deep-learning model was created with EarlyStopping and ModelCheckpoint to prevent overfitting and was evaluated using stratified k-fold cross-validation ($k = 5$). The model was trained and tested using training data and validation data from each fold. The model's performance was assessed using a confusion matrix, receiver operating characteristic curve, and area under the curve. The average performance metrics obtained from each cross-validation were determined. For the analysis of feature importance, SHAP, permutation feature importance, and LIME were employed as model-agnostic explanation methods.

Results: The deep-learning model proved effective in distinguishing from sarcopenia, with an accuracy of 87.55%, precision of 85.57%, recall of 90.34%, and F1 score of 87.89%. Waist circumference (WC, cm), absolute grip strength (kg), and body fat (BF, %) had an influence on the model output. SHAP, LIME, and permutation feature importance analyses revealed that WC and absolute grip strength were the most important variables. WC, figure-of-8 walk, BF, timed up-and-go, and sit-and-reach emerged as key factors for predicting possible sarcopenia.

Conclusion: The deep-learning model showed high accuracy and recall with respect to possible sarcopenia prediction. Considering the need for the development of a more detailed and accurate sarcopenia prediction model, the study findings hold promise for enhancing sarcopenia prediction using deep learning.

KEYWORDS

deep learning, stratified k-fold, sarcopenia, physical fitness, aging, prediction

1. Introduction

Sarcopenia is a severe health problem characterized by a reduction in muscle quality and quantity (1–4), leading to a decline in physical fitness and strength. The reduced quality of life and diminished functionality are the primary concerns associated with sarcopenia (2), which can increase societal costs and individual health concerns (5–7), thereby highlighting the importance of early prevention and treatment for sarcopenia.

A decline in physical fitness has been shown to be highly related to the incidence and mortality of sarcopenia (8). Previous studies reported that a lower level of absolute grip strength (upper strength) (9), lower level of strength on the chair sit-and-stand test (10), lower level of flexibility on the sit-and-reach test (11), lower level of cardiorespiratory endurance on the 2-min step test (12), lower level of balance on the 3-m timed up-and-go (TUG) test (13), and lower level of coordination on the figure-of-8 walk test (14) were highly associated with the diagnosis and prediction of sarcopenia. However, accurately measuring various aspects of physical fitness and understanding how they influence each other and contribute to the risk of sarcopenia remains a significant challenge in predicting sarcopenia.

Deep neural network (DNN) and machine learning (ML) algorithms have been proposed to overcome the challenges in accurately predicting sarcopenia using blood markers and skeletal muscle images (7, 11, 15–20). On the one hand, an ML model based on support vector regression, decision tree, random forest regression, or extreme gradient boosting has been used to predict physical fitness variables in older adults (15, 17, 20). On the other hand, a deep-learning-based model has been utilized to analyze computed tomography images and predict sarcopenia, and this model has also been reported to effectively predict the quality and strength of muscles in patients with cancer (21). Furthermore, a previous study developed a deep-learning-based sarcopenia prediction model (wide and deep) using clinical laboratory markers (22), which demonstrated high accuracy (area under curve [AUC] score), as compared with that of ML model prediction methods (support vector regression, random forest regression, and extreme gradient boosting). Additionally, deep learning applications in healthcare are rapidly evolving (23–25), with significant advancements in sarcopenia classification models using computed tomography (CT) (23). Several studies have used ML models to predict sarcopenia using laboratory markers and muscle mass measurements or images, without incorporating physical fitness variables (24, 26). Therefore, many subjects with sarcopenia are required to analyze and predict deep-learning models of the details of physical fitness variables.

Physical fitness is regarded as a significant indicator of sarcopenia. Nonetheless, previous studies have attempted to predict sarcopenia by measuring only the muscle quantity and blood markers without physical fitness (7, 11, 15, 18, 22). Applying a deep-learning model could provide an accurate approach to predicting sarcopenia by analyzing physical fitness and its relationships. Additionally, the accurate prediction of sarcopenia is challenging without considering physical fitness as blood markers and muscle quantity alone are insufficient indicators. Therefore, the present study aimed to develop and analyze a deep-learning model for predicting the decline in physical fitness due to sarcopenia in individuals with potential sarcopenia. This research sought to accurately predict physical fitness using a deep-learning model and to propose effective preventive and treatment strategies against sarcopenia.

2. Materials and methods

2.1. Dataset

For this type of study, formal consent was not required. The dataset was approved by the Research Ethics Committee of Hyupsung University (IRB no: 7002320-202303-HR-001), and all methods were performed in accordance with the relevant guidelines.

The present study used the 2010–2023 Korean National Physical Fitness Award data. The data comprised exercise- and health-related measurements in Koreans aged >65 years and were collected from 19 national fitness centers. The original Korean Fitness Award data were collected from Jan 2010 to Mar 2023 ($n = 1,545,313$), and the first stage excluded data from persons aged <64 years ($n = 1,416,249$). In the second stage, data of individuals with >20% missing values ($n = 619$) were excluded along with values > Q3 + 1.5*IQR or < Q1–1.5*IQR (Q, quartile; IQR, interquartile range; $n = 20,141$). The final sample size was a 108,304 participants (Figure 1). All participants voluntarily participated in the Korean National Physical Fitness Award Project through the national fitness center in each region. Body mass index (BMI, kg/m^2), body fat (BF, %), and waist circumference (WC, cm), and physical fitness variables, such as absolute grip strength (kg), chair sit-and-stand up (counts), sit-and-reach (cm), 2-min step (counts), 3-m TUG (sec), and figure-of-8 walk (sec) (7, 11, 18), were all measured in Koreans aged >65 years. Specific measurements were conducted by trained physical fitness instructors (27) and were performed on the basis of the Survey of National Physical Fitness (7, 11, 18) and Development of National Physical Fitness Certification Standards for older adults (7, 11, 18). The analysis environment was Apple M1 Max with macOS Ventura 13.4, 32 GB RAM, and NVIDIA A100-SXM4-40GB. The analysis program was Google Colaboratory (Colab) with a cloud-based platform that offered high GPU for computing purposes, which was based on Python 3.10.11 (28).

2.2. Data variables and data collection

In this study, the appendicular muscle mass (ASM, kg) was quantified and estimated using high-quality anthropometric formulas (4, 6, 29). The ASM ($R^2 = 0.90$, standard error = 1.35 kg) was calculated as 0.193*Weight (kg) + 0.107*Height (cm) – 4.157*sex (1 for male, 2 for female) – 0.037*Age (years) – 2.631 (29). ASM/ht^2 was calculated as a measure of ASM adjusted for the square of height in meters, and the ASM/ht^2 value of the 20th percentile was used to define low muscle mass, similar to previous studies (1–3). In this study, low muscle mass was defined as an ASM/ht^2 value of <6.54 for men and <5.14 for women. The 20th percentile was subsequently divided into two categories: normal ($n = 103,546$) and potential sarcopenia ($n = 5,357$). The binary dependent (normal vs. possible sarcopenia) variable was predicted using independent variables, including BF (%), WC (cm), and physical fitness measures such as sit-and-stand up (counts), 2-min step (counts), TUG (sec), figure-of-8 walk (sec), absolute grip strength (kg), and sit-and-reach (cm). Table 1

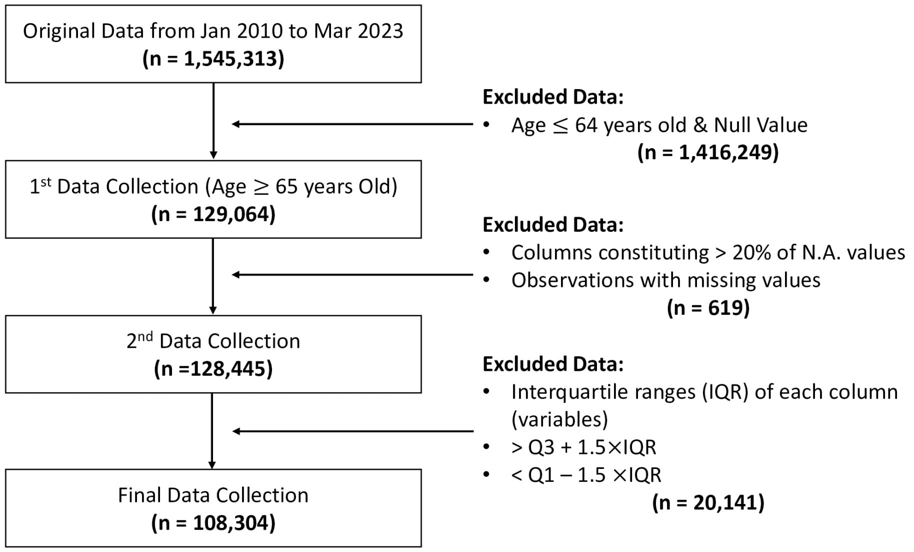


FIGURE 1
This figure indicated how the data collection in this study. From original data from January 2010 to March 2023 was 1,545,313 subjects. This study conducted excluded data following the 2.2 Data variables and data collection section. The number of final data collection was 108,304 subjects.

summarizes all variables of this dataset between normal and possible sarcopenia, whereas Figure 1 presents how the data were collected.

2.3. Statistical modeling

2.3.1. Data normalization and sampling

The data were normalized using MinMaxScaler to avoid overreliance on certain features while speed learning by restricting all variables to a range between 0 and 1. Datasets were also balanced via under-sampling using RandomUnderSampler by reducing oversampling between "possible sarcopenia" and "normal."

2.4. Data analysis

2.4.1. Stratified k-fold cross-validation

In this study, the dataset was divided while maintaining the same class ratio, which is particularly effective for imbalanced datasets. Five equal-size groups ($k = 5$) were used, and the data were randomly shuffled; hence, each model underwent five independent training–evaluation processes to ensure the reproducibility and reliability of the data results. Additionally, the performance metrics obtained from these processes were averaged to estimate the final performance of the model (30–32).

2.4.2. Model structure and compilation

In this study, a neural network model with four layers was created. The initial layer consisted of 64 nodes; for the initial layer, the rectified linear unit (ReLU) activation function was implemented as its activation function. The input data were organized as an eight-dimensional vector to accommodate for datasets with eight independent variables. A dropout layer was employed to prevent overfitting; as part of its learning process, this layer randomly deactivated 20% of nodes within this layer during each iteration to ensure that the model did not overrely on specific nodes and to help increase the generalization capability. The third layer comprised 32 nodes using the ReLU activation function. Finally, an individual node layer was equipped with the sigmoid function to produce probabilities between 0 ("normal") and 1 ("possible sarcopenia"), catering specifically to binary classification problems. At the compilation stage, binary cross-entropy was utilized as the loss function, providing an appropriate measure for binary classification problems by quantifying differences between predicted and actual values of models. Adam optimizer was selected as the optimization algorithm owing to its adaptive learning rate adjustment that could enhance the learning speed and overall performance. Accuracy was selected as the performance metric for evaluating the precision of classification predictions. Subsequently, this model was employed to learn from training data at each step, followed by validation data performance evaluation. This process was iterated five times using a five-fold cross-validation methodology (5, 33).

2.4.3. EarlyStopping and ModelCheckpoint

EarlyStopping monitors validation loss and halts the training when validation loss does not improve after a certain number of epochs (in this study, a patience parameter = 20). This strategy prevents overfitting because it stops the training when the performance of the validation set starts to degrade. Moreover, the weights of the model at its peak performance are restored by setting the best weight, thereby ensuring the retention of the best model instead of the final one when the training has ceased. ModelCheckpoint also monitors validation loss, with the model being saved at each time when validation loss decreases during training. This strategy preserves the best performing model after the training has been completed (34, 35).

2.4.4. Model training and test

Training data from each fold, as well as validation data, were used to train a model (80% of training data, 20% of validation data). The training processes were 200 epochs in length, with 16 batches of data per training run. During training, EarlyStopping and ModelCheckpoint

TABLE 1 The results of differences between normal and possible sarcopenia.

Variables	Normal (n = 102,919)	Possible sarcopenia (n = 5,385)	t	p-value
Age (years)	71.37± 4.77	74.18 ± 5.58	−41.67	0.000
Gender (M = 1/F = 2)	1.57 ± 0.50	1.90 ± 0.30	−48.04	0.000
ASM/ht^2 (kg/m^2)	6.75 ± 0.98	5.04 ± 0.50	126.59	0.000
Height (cm)	158.58 ± 8.13	151.75 ± 7.14	60.44	0.000
Weight (kg)	62.23 ± 8.39	45.27 ± 3.25	147.76	0.000
Waist circumference (cm)	84.67 ± 7.38	72.80 ± 5.12	116.61	0.000
Absolute grip strength (kg)	25.49 ± 7.79	18.98 ± 5.01	60.69	0.000
Sit and reach (cm)	10.63 ± 8.77	12.14 ± 7.97	−12.38	0.000
Body fat (%)	31.01 ± 7.40	25.80 ± 6.25	50.71	0.000
BMI (kg/m^2)	24.73 ± 2.60	19.72 ± 1.61	140.04	0.000
Sit and stand (count)	20.70 ± 5.82	19.46 ± 5.71	15.26	0.000
2-min step (count)	110.43 ± 17.59	105.02 ± 19.23	21.89	0.000
TUG (sec)	6.01 ± 1.11	6.40 ± 1.24	−24.95	0.000
Fig-8 walk (sec)	24.60 ± 4.77	26.11 ± 5.24	−22.63	0.000

This table described the results of differences between normal (n = 102,919) and possible sarcopenia (n = 5,385). All statistical analysis was based on an independent t-test and the statistical ± < 0.05. ASM/ht^2, Appendicular skeletal muscle/square of height; BMI, Body mass index; 2-min step, 2 min step test; TUG, 3-m up-and-go test; Fig-8 walk, Figure-of-8 walk test.

calls were employed to monitor validation loss during learning sessions. Once loaded onto the validation data, it was subsequently predicted using this model. Results were outputted as probabilities prior to binary classification using a threshold of 0.5% (36).

2.4.5. Model prediction and performance evaluation

The model's performance was visually evaluated using a confusion matrix. Receiver operating characteristic (ROC) curves were constructed, and the AUCs were calculated. The average performance metrics obtained from each cross-validation were determined and outputted. Changes in the model's performance were visualized on a graph showing accuracy, precision, recall, and F1 scores obtained from cross-validation (37, 38).

2.4.6. Model interpretability and explanation with SHAP, permutation feature importance, and LIME

After assessing the model's performance, SHapley Additive exPlanations (SHAP) (39), permutation feature importance (40), and Local Interpretable Model-Agnostic Explanations (LIME) (41) were employed as model-agnostic explanation methods for evaluating how the model's prediction worked, which provided insights into which features contributed the most toward making predictions to enhance the transparency and accuracy within models.

3. Results

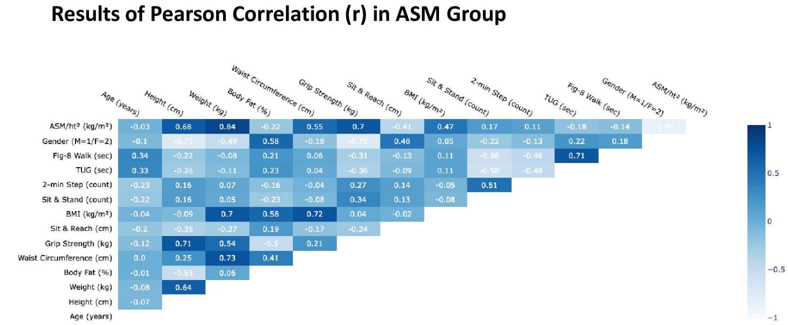
3.1. Results for all variables between normal and possible sarcopenia

All variables showed statistically significant differences between normal (n = 102,919) and possible sarcopenia (n = 5,385). For the results, a negative t-statistic value suggested that the mean value was higher in possible sarcopenia than in normal. Statistically negative values were obtained for age (t = −41.67), gender (−48.04), sit-and-reach (t = −12.38), TUG (t = −24.95), and figure-of-8 walk (t = −22.63), indicating that these variables were higher in possible sarcopenia (Table 1).

3.2. Results for multicollinearity using Pearson's correlation, variance inflation factor, and tolerance

In this study, Pearson's correlation (r) threshold >0.70, VIF threshold ≥5, and tolerance threshold ≤0.01 indicated multicollinearity; related features were subsequently removed. Pearson's correlation coefficient of ASM/ht^2 was >0.70 for weight and gender (Figure 2). The VIF and tolerance values for weight (VIF = 158.76, tolerance = 0.006) and gender (VIF = 114.64, tolerance = 0.009) were > 5 and < 0.1, respectively. Similarly, VIF and tolerance values for BMI (VIF = 162.80, tolerance = 0.006) and height (VIF = 90.68, tolerance = 0.011) were >5 and <0.1, respectively (Figure 2B). Pearson's correlation coefficient for the absolute grip strength was 0.70; however, the VIF and tolerance values were 3.21 and 0.311, respectively, suggesting that the absolute grip strength did not exhibit multicollinearity. Hence, in this study, weight, height, BMI, and gender were excluded as variables due to multicollinearity, and ASM was practically quantified using an anthropometric equation based on gender, age, weight, and height. Age was excluded from the deep-learning model. Therefore, this study included independent variables, including BF (%); WC (cm); and physical fitness measures such as sit-and-stand up (counts), 2-min step (counts), TUG (sec), figure-of-8 walk (sec), absolute grip strength (kg), and sit-and-reach (cm).

A



B

Results of VIF & Tolerance in Variables

Variables	VIF Factor	Tolerance
const	1617.29	0.001
ASM/ht² (kg/m²)	181.02	0.006
BMI (kg/m²)	162.80	0.006
Weight (kg)	158.76	0.006
Gender (M=1/F=2)	114.64	0.009
Height (cm)	90.68	0.011
Body Fat (%)	3.47	0.288
Grip Strength (kg)	3.21	0.311
Waist Circumference (cm)	3.11	0.322
TUG (sec)	2.38	0.421
Age (years)	2.28	0.438
Fig-8 Walk (sec)	2.27	0.440
Sit & Stand (count)	1.88	0.531
2-min Step (count)	1.50	0.668
Sit & Reach (cm)	1.47	0.679

FIGURE 2
(A,B) described the multicollinearity in *Pearson* correlation, variance inflation factor (VIF), and tolerance. The *Pearson* Correlation (*r*) had a threshold over absolute 0.70, and then VIF threshold ≥5 and Tolerance ≤0.01 had multi-collinearity, and then remove the related features. A high density of blue color mean highly correlated in individual variables. const, constant of VIF and tolerance; ASM/ht2, Appendicular skeletal muscle/square of height; BMI, Body mass index; 2-min Step, 2 min step test; TUG, 3-m up-and-go test; Fig-8 Walk, Figure-of-8 walk test.

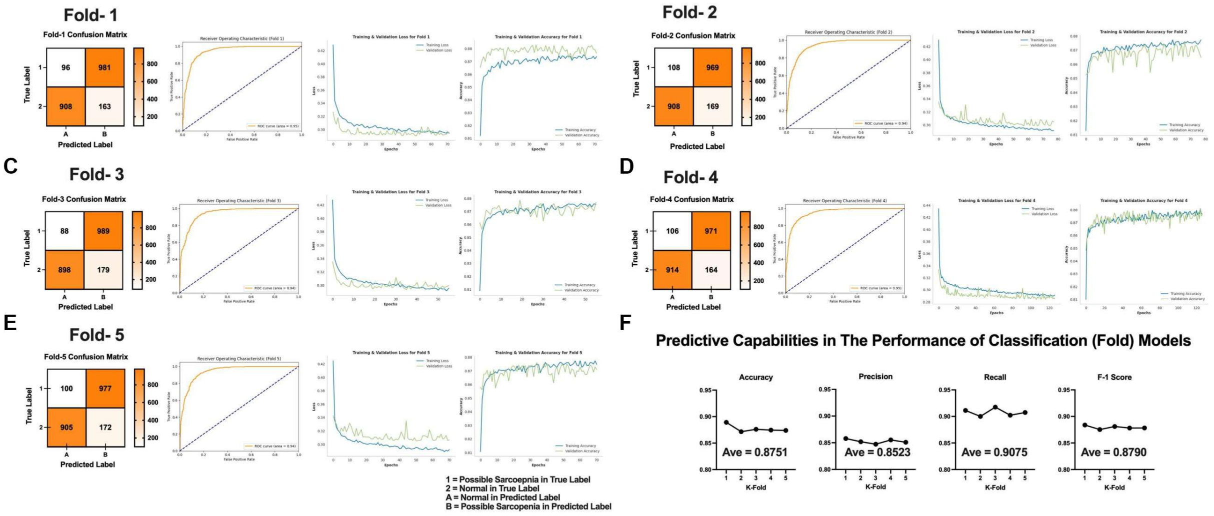


FIGURE 3
This figure showed the confusion matrix, AUC curve, and visualizing loss and accuracy for training and validation data in each fold. ROC-AUC, Receiver Operating Characteristic Curve—Area Under Curve. **(A)** Fold-1. **(B)** Fold-2. **(C)** Fold-3. **(D)** Fold-4. **(E)** Fold-5. **(F)** Predictive capabilities in the performance of classification (fold) models.

3.3. Results for the confusion matrix from the stratified k-fold cross-validation

Fold-1 had early stopping in 72 epochs (ROC-AUC, 0.95), with a train loss value of 0.2940, train accuracy of 0.8738, validation loss value of 0.2950, and validation accuracy of 0.8765 (Figure 3A). Fold-2 had early stopping in 78 epochs (ROC-AUC, 0.94), with a train loss value of 0.2919, train accuracy of 0.8773, validation loss value of 0.3048, and validation accuracy of 0.8649 (Figure 3B). Fold-3 had early stopping in 56 epochs (ROC-AUC, 0.94), with a train loss value of 0.2957, train accuracy of 0.8755, validation loss value of 0.2997, and validation accuracy of 0.8770 (Figure 3C). Fold-4 had early stopping in 127 epochs (ROC-AUC, 0.95), with a train loss value of 0.2914, train accuracy of 0.8766, validation loss value of 0.2853, and validation accuracy of 0.8760 (Figure 3D). Finally, Fold-5 had early stopping in 71 epochs (ROC-AUC, 0.94), with a train loss value of 0.2921, train accuracy of 0.8747, validation loss value of 0.3065, and validation accuracy of 0.8709 (Figure 3E). The mean squared error from each fold was 0.0911, the mean average error was 0.1813, and average ROC-AUC was 0.9445 (Figure 3F).

3.4. Results for the deep-learning model from the stratified k-fold cross-validation

As shown in Figure 3F, the deep-learning model was trained and evaluated on our dataset using stratified k-fold cross-validation ($k = 5$). Biases in training and validation data were minimized by partitioning the data into training and verification sets while preserving the overall distribution patterns. "Normal" and "possible sarcopenia" were differentiated using "0" and "1" as indicators of normality. Our performance metrics indicated that the model exhibited an accuracy of 0.8751, implying that the model made correct predictions in 87.51% of all cases and that the model accurately classified "normal" and "possible sarcopenia." The precision score was 0.8523, indicating a high degree of precision in prediction for the positive class ("possible sarcopenia"). In other words, 85.23% of the instances predicted as "possible sarcopenia" were indeed correctly identified. The recall score for the model was 0.9075, highlighting the model's ability to accurately identify a high proportion of actual positive cases. That is, the model was able to correctly classify 90.75% of all actual cases of "possible sarcopenia."

The F1-score takes both precision and recall into account and is, thus, a useful metric for evaluating the balance between the two, with a high F1-score indicating good model performance. The F1-score for our model, which is the harmonic mean of precision and recall, was 0.8790. As our model showed a high score of 87.9%, this model therefore exhibited overall high performance in classifying between "normal" and "possible sarcopenia."

3.5. Results for SHAP, LIME, and permutation feature importance

The SHAP results indicated that WC, absolute grip strength, and BF had a high impact on model output (Figures 4A,B). Small WC, low absolute grip strength level, and low BF level were more likely to be indicative of possible sarcopenia [Figure 4A (left), with low values for features in blue color]. Specific SHAP feature importance values are presented in Figure 4A (right); WC showed the highest importance, with a SHAP value and prediction value of 0.2170 and 0.8046, respectively. These results suggested that WC had the greatest impact on prediction. The second most important variable was absolute grip strength, with an importance value and prediction value of 0.1408 and 0.9845, respectively. The third most important variable was BF (%), with an importance value and prediction value of 0.1027 and 0.2690, respectively. The SHAP values and prediction values of the remaining variables were as follows: figure-of-8 walk (importance: 0.0265, prediction: 0.0002), TUG (importance: 0.0176, prediction: 0.0655), 2-min step (importance: 0.0100, prediction: 0.8836), sit-and-reach (importance: 0.0082, prediction: 0.9794), and sit-and-stand (importance: 0.0078, prediction: 0.1620).

The permutation feature importance results indicated that WC exhibited the highest importance in permutations, with an importance score of 0,1979 (standard deviation [SD]: 0.0048) (Figure 4B), suggesting that it had a significant impact on model predictions. The second most important variable was absolute grip strength, with an importance score of 0.1067 (SD: 0.0075), whereas the third most important variable was BF, with an importance score of 0.0668 (SD: 0.0070). The permutation importance values of the remaining variables were as follows: 0.0075 for figure-of-8 walk (SD: 0.0020), 0.0040 for TUG (SD: 0.0017), 0.0038 for sit-and-reach (SD: 0.0015), 0.0037 for 2-min step (SD: 0.0024), and 0.0024 for sit-and-stand (SD: 0.0020).

The LIME results revealed that WC (cm, 0.46) contributed the most to the prediction of possible sarcopenia (Figure 4C). A smaller WC exerted the greatest influence on prediction, followed by the figure-of-8 walk (sec, 0.07), BF (%, 0.06), TUG (sec, 0.04), and sit-and-reach (sec, 0.03). These three variables contributed more to prediction, as their values increased with possible sarcopenia. Conversely, absolute grip strength (kg, 0.03) and sit-and-stand (counts, 0.01) contributed less to prediction because as the values of these variables increased, the prediction value (normal) decreased. Finally, sit-and-reach (cm) was shown to make a weak positive contribution to prediction within a certain range.

The prediction value of probabilities was 0.89 in possible sarcopenia after LIME feature importance [Figure 4C (right)]. The

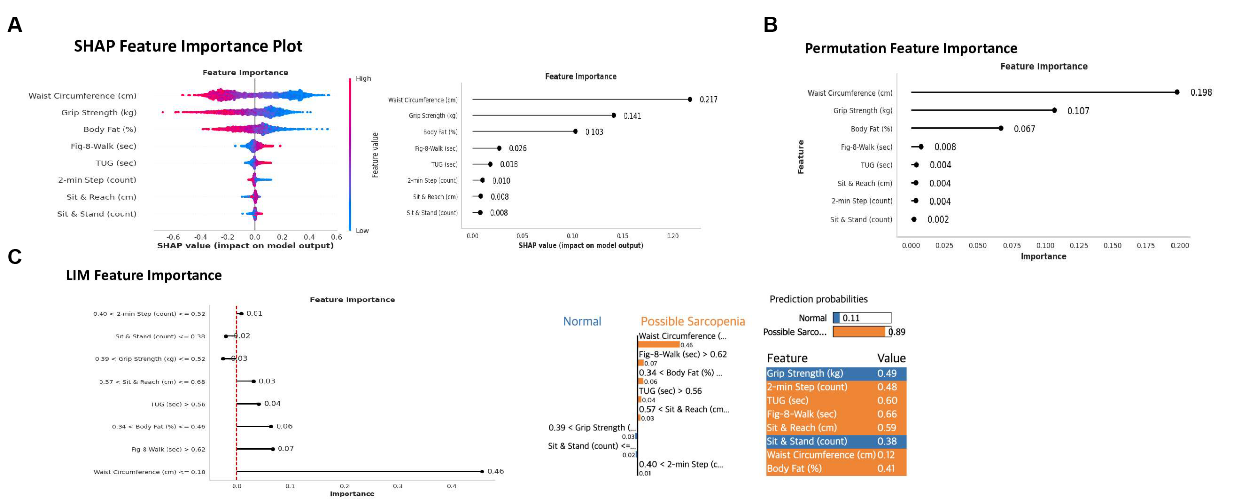


FIGURE 4
This figure showed the model-agnostic explainable algorithms from the deep learning model. The **(A)** explained feature importance from Shapley Additive exPlanations (SHAP) in the best model. The blue color mean low level impact on the model, and red coler mean high level impact on the model. The **(B)** explained permutation feature importance in the best model. The **(C)** explained Local Interpretable Model-Agnostic Explanations (LIME) feature importance in the best model and used HyperText Markup Language (HTML). Grip strength, Absolute grip strength; 2-min Step, 2 min step test; TUG, 3-m up-and-go test; Fig-8 Walk, Figure-of-8 walk test.

variables related to "possible sarcopenia" prediction in the model were WC (cm), figure-of-8 walk (sec), BF (%), TUG (sec), and sit-and-reach (cm). The WC of values less than 0.18, which mean original values using MinMaxScaler, was 71.49 cm. Its value mean less than 71.49 cm of WC values to be a possible sarcopenia. The figure-of-8 walk (sec) of values were over 0.62, which mean 28.45 s in original value to be a possible sarcopenia. The range of BF (%) were over 0.34 and less than 0.46, which mean over 23.96% and less than 29.16% of BF to be a possible sarcopenia. The TUG also had over 0.56, which mean 6.70 s in original value to be a possible sarcopenia. The sit-and-reach (cm) had range over 0.57 to less than 0.68, which revealed 13.91–19.36 cm to be a possible sarcopenia.

4. Discussion

The present study used a deep-learning model to predict sarcopenia and evaluated the performance of this model using stratified k-fold cross-validation (Figure 3). The average accuracy, precision, recall, and F-1 score of our model were 87.51, 85.23, 90.75, and 87.90%, respectively, suggesting that this model can accurately distinguish normal from sarcopenia cases. In this study, we employed SHAP, LIME, and permutation feature importance methods to analyze feature importance. Through this, we found that WC (cm), absolute grip strength (kg), and BF (%) had the greatest impact on possible sarcopenia prediction, indicating that WC, absolute grip strength, and BF play a significant role in predicting possible sarcopenia and may be used to assess sarcopenia. Notably, WC emerged as the most important variable in predicting possible sarcopenia. These results can be supported deep-learning based model had diagnostic sarcopenia (22).

Our study used ASM/ht^2 <6.54 (kg/m^2) for men and <5.14 (kg/m^2) for women, which supported a similar pattern of cut-off values by the Asian Working Group for Sarcopenia (3). While an anthropometric equation was used in this study to estimate ASM, the results showed a similar pattern to the findings of previous studies using the criteria cut-off value (3, 4, 29). The results also supported that a DNN based on CT-based skeletal muscle measurement was highly related to sarcopenia prediction (14, 23, 25). Based on the previously established formula of ASM (29), this study found that the accuracy of the deep-learning model in predicting sarcopenia was higher when using ASM/ht^2, thus, supporting the potential of using physical fitness measures to predict sarcopenia.

In a previous study on data from the Korea National Health and Nutrition Examination Survey (KNHANES) conducted from 2008 to 2011, the dataset also suggested that the DNN had a significant impact on physical activity, BMI, and WC using SHAP analysis in the sarcopenia prediction model (26). The SHAP feature importance (Accuracy 84%) with the DNN model showed that WC and BMI had the highest impact on the DNN prediction model with physical activity level in daily life (26). Our results also indicated that WC and absolute grip strength were the most important features in predicting possible sarcopenia, which is a similar pattern of results that are able to explain the higher accuracy of the deep-learning model compared to that of the ML method.

Moreover, the same dataset of a previous study using Korean National Fitness Award from 2015 to 2019 indicated that DNN model represented the best performance among physical fitness variables (15–17). The study explained that including the grip strength variable as a marker of physical fitness improved the prediction of the DNN (Accuracy: 78.4%). Our deep-learning model revealed that absolute grip strength was the key variable factor in predicting possible sarcopenia (Accuracy: 87.55%); the accuracy improved by 9.15% in our study because of early stopping and using the model checkpoint method, which improved model performance and efficiency (42, 43).

Similar to previous study, our study used the same dataset and our deep-learning model was more valid through under-sampling method and stratified k-fold analysis (5, 31, 32, 44). The results supported our results, which revealed that WC (cm) and absolute grip strength had a high impact on the DNN model with SHAP, LIME, and permutation analysis (Figure 4). Moreover, WC prediction using models based on extreme gradient boosting was significantly important for epidemiology (6, 44); hence, our results suggested more details of WC with physical fitness and were similar to those of previous studies. When compared with our previous study, the result indicated that ML with CatBoost Regressor showed a good prediction of grip strength in older adults [Mean Squared Error (MSE) = 16.659]; among the seven ML models tested, it achieved the highest accuracy. However, in this study, the deep-learning model using stratified k-fold validation outperformed all others with the lowest MSE value of 0.0911. This result substantiated the superiority of the deep-learning approach over the ML approach in terms of accuracy (45).

Our study indicated that WC had a high impact on possible sarcopenia prediction (Figure 4). This result supported that sarcopenia was related to metabolic syndrome in men with normal WC and women with high WC and was predicted by abdominal obesity (46). Our SHAP and permutation feature importance analysis results also supported that WC contributed to the risk of sarcopenia with metabolic syndrome (46). The LIME analysis showed that WC had a value of less than 0.18 (original value = 71.49 cm) and the BF value ranging from 0.34 to 0.46 (original value = 23.96–29.16%) was related to possible sarcopenia. This result suggested that high WC and BF were significantly related to a lower incidence of sarcopenia (47). Moreover, the sarcopenia classification from an anthropometric method showed that WC was useful in screening for possible sarcopenia (48). This result supported our study, which considered the strong association of WC with the anthropometric method to predict possible sarcopenia. A previous study, who were in sarcopenia defined by the Asian Working Group for Sarcopenia (AWGS), showed only women with high WC and BF group had a lower incidence of sarcopenia (47). Our study also indicated that lower levels of WC and BF highly predicted possible sarcopenia (Figure 4A). When compared to the previous study, our study excluded gender variable in the results of multicollinearity (Figure 2), and the results of WC and BF from our study would change the importance factor within the gender difference. Furthermore, the deep-learning-based regression was useful for predicting grip strength in the upper strength by reducing the risk of musculoskeletal disorders (49). Our SHAP and permutation feature analysis results also supported that grip strength was the second most important variable for predicting possible sarcopenia. In addition, our deep neural prediction model had predicted that absolute grip strength had a high impact on predicting a possible sarcopenia (50). Grip strength was a valid and easy tool for early screening of sarcopenia (15–17, 51) and was highly related to physical fitness variables (15–17). Our study also demonstrated that the LIME analysis, as shown in Figure 4, indicated that the absolute grip strength ranging from 0.39 to 0.52 (original value = 19.71–25.68 kg) was associated with the normal group. Table 1 described the absolute grip strength in the possible sarcopenia group as 18.89 kg. A previous study described that grip strength (kg) was more diagnostic of sarcopenia than the chair stand test (count) (52). Our results are consistent with this, showing grip strength to be the second most important variable for predicting possible sarcopenia, in comparison to other physical fitness variables. However, according to AWGS guidelines, the grip strength for diagnosing sarcopenia was less than 28.0 kg for men and less than 17.7 kg for women (53). Our results would consider the gender difference in absolute grip strength, the importance of grip strength in the AWGS criteria would change.

The present study has some limitations. First, the defined possible sarcopenia in this study based only on the anthropometric formulas (muscle mass only) without considering muscular strength and physical function. This fundamentally differs from the diagnostic criteria by AWGS, which considers muscular strength and physical function with muscle mass. Our findings may not fully reflect the broader aspects of sarcopenia as defined by the AWGS criteria. Therefore, this limitation should be considered when interpreting and applying the results of our study. Further studies are required to analyze direct measurements of ASM/ht^2 with physical fitness. Second, future research may incorporate additional variables, such as physical activity level and nutritional status, to improve the accuracy of the estimation results. Third, the deep-learning model used in this study showed relatively high accuracy, precision, recall, and F1 scores; however, these results do not preclude the possibility of model overfitting. While various cross-validation techniques were employed to mitigate this issue, such techniques cannot always completely prevent overfitting. Lastly, the results of this study indicated that WC, absolute grip strength, and BF play an important role in predicting sarcopenia. However, the measurement of these variables typically involves a complex process that requires professional training, which may limit their practicality in diagnosing and managing sarcopenia. Further research based on the results of this study is required to identify other variables that are easier to measure but can still provide meaningful information.

In conclusion, the results from stratified k-fold cross-validation indicated that our model exhibited high performance, with an average accuracy of 87.55%, precision of 85.57%, recall of 90.34%, and F1 score of 87.89%. These results suggest that this model can accurately classify the majority of normal and possible sarcopenia cases. Additionally, the SHAP, LIME, and permutation feature importance analysis revealed that WC, absolute grip strength, and BF had the greatest impact on model prediction for possible sarcopenia. WC, in particular, was deemed to be the most important variable. The deep-learning model exhibited high accuracy and recall in sarcopenia prediction, holding promise for enhancing sarcopenia prediction using deep learning. Nonetheless, there remains a need for the development of a more detailed and accurate sarcopenia prediction model. This would provide important insights for the prediction and management of sarcopenia and can be used in future research in this field.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Ethics statement

The studies involving humans were approved by the Research Ethics Committee of Hyupsung University (IRB no.: 7002320-202303-HR-001), and all methods were performed in accordance with the relevant guidelines. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

J-HB and DK contributed to data collection, data analysis, and writing of the manuscript. J-HB, J-wS, and DK were involved in data collection and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1241388/full#supplementary-material

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Social interaction trajectories and all-cause mortality in older adults: the Otassha study

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Introduction: This longitudinal study aimed to identify aging trajectory patterns of social interaction by sex and determine the association between these patterns and all-cause mortality.

Methods: Participants were 4,065 community-dwelling older adults (1849 men) in Japan, aged 65–89 years, who responded twice or more to a mail survey conducted between 2012 and 2020. Social interaction was examined through the frequency of face-to-face and non-face-to-face contact with non-resident family and friends. The aging trajectories of the social interaction scores were identified using group-based trajectory modeling.

Results: Two groups were identified among both men and women. Among men with high-frequency interaction, a rapid decrease in the frequency of social interaction was observed after 80years of age. Conversely, among women, the frequency tended to remain the same, even after 80years of age. The social interaction score among those aged 65years in the low-frequency group was approximately 4 points for men and 6 points for women. Among men, no decrease was observed; however, it tended to decline after 85years of age among women. Among men, the factors associated with the low-frequency group were instrumental activities of daily living score, perceived financial status, and social participation, while among women, they were self-rated health and social participation. The adjusted hazard ratio in the low-frequency group for all-cause mortality was 1.72 (95% confidence interval, 1.27–1.72) for men and 1.45 (95% confidence interval, 0.98–2.14) for women.

Discussion: In the low-frequency group, men had a higher risk of all-cause mortality than women. Daily social interaction from mid-age is important to reduce the risk of social isolation and all-cause mortality in later life.

KEYWORDS

all-cause mortality, community-dwelling older adults, group-based trajectory modeling, social interaction, social isolation

1. Introduction

Maintaining social interaction with others by meeting and talking to them is important as it helps improve health status. Social isolation is assessed using various measurements such as the number and frequency of social interaction, the social support from others, and the range of contact persons (1); one aspect of social isolation considers it a state of deteriorated social interaction (2). Social isolation is associated with the incidence of cardiovascular diseases (3), dementia (4), long-term care (5), and mortality (6, 7). Thus, maintaining social interaction is crucial for healthy longevity.

Objective measures of social isolation include the number of people with whom a person interacts (8) and the frequency of interaction (9). These two factors decline with an increase in age (8, 9), suggesting that social interaction declines gradually with age, leading to isolation. This could result from decreased mobility because of physical deterioration (10), decreased cognitive function (11), and age-based decreased social participation (12). Further, poor self-rated health and decreased social participation are risk factors for social isolation (1). Deterioration of health status and reduced opportunities for social participation based on age may accelerate the decline in the frequency of social interaction and the incidence of social isolation. However, the trajectory of the decline in the frequency of social interaction is not fully understood.

Studies have identified aging trajectories using group-based trajectory modeling for longitudinal data (13–18). This method can classify the patterns of an outcome's evolution over age or time from fragmental data (19). Regarding physical performance and higher-level functional capacity in older individuals, several trajectory patterns, such as a pattern with gradual decrease with age, a pattern with rapid decrease, and a pattern with a decrease during the early phase, were observed (17, 18). Such age-related declines in physical function may rapidly decrease social interaction. One study showed that social network size declined with age (20), especially in later life; however, it did not clarify the patterns of the decline of social network size with aging. Additionally, a previous study reported sex-related differences in the association between social isolation and functional decline (21); however, sex-related differences in the trajectories of social interaction are unclear. To our knowledge, no studies have identified the aging trajectory patterns of social interaction by sex. A recent systematic review assessing the factors of social isolation revealed that compared to women, men have higher risk for social isolation (1), suggesting that reduced social interaction is also likely to be more pronounced in men. Identifying these trajectories can help determine how social interaction decreases with age and leads to isolation. Examining the factors associated with such trajectories and their impact on health outcomes can provide useful insights into preventive measures against social isolation.

Therefore, this study aimed to identify the aging trajectory of social interaction frequency by sex—a measure of social isolation—using longitudinal data from a cohort of community-dwelling Japanese older adults. Furthermore, the factors associated with trajectory patterns and the relationship between such patterns and all-cause mortality were examined. In this study, we hypothesize that the aging trajectory patterns of social interaction frequency differ by sex, including patterns with rapid decrease such as physical function.

2. Materials and methods

2.1. Participants

Data were obtained through a mail survey conducted between 2012 and 2020 from the Otassha Study. In the cohort study, participants were sampled from over 7,000 residents aged 65–85 years who lived in nine areas near Itabashi-ward, Tokyo, Japan, excluding institutionalized residents and participants of previous surveys conducted by our institute. Inclusion and exclusion criteria were residents described above who responded to the survey and did not respond, respectively. Details of this cohort are described elsewhere (22).

In the 2012 first mail survey (Wave 1), a questionnaire was sent to 7,015 older residents. Of these, 3,696 responded (response rate: 52.7%). In 2013 and 2014, new participants aged 65 years were added, and second and third mail surveys (Waves 2 and 3) were conducted. Although follow-up surveys were not conducted in 2015 and 2016 due to limited research funds, annual surveys were conducted with the past respondents and new participants aged 65 years from 2017 to 2020 (Waves 4–7; Table 1). The inclusion criterion for the present study was participants who completed the items on social interaction at least twice during the seven surveys. Finally, 81.8% of the first mail survey participants were included in the analysis of this study. Although there was no significant difference in the men to women ratio between participants and dropouts, the age of the dropouts (74.5 years) was significantly higher than that of the participants (72.7 years). Other missing data were handled by the group-based semiparametric mixture modeling.

All respondents of the mail survey provided written informed consent to use their data for this study. Ethical approval for this study was granted by the ethics committee of the Tokyo Metropolitan Institute of Gerontology (no. R21-033). The study was conducted following the guidelines of the World Medical Association Declaration of Helsinki.

2.2. Social interaction score

Social interaction was assessed by asking participants about the frequency of face-to-face or non-face-to-face contact with non-resident family and friends (5, 9). The following four questions were asked: (i) "How often did you see your family members or relatives who are living apart?" (ii) "How often did you make contact with your family members or relatives who are living apart by phone, email, or facsimile?" (iii) "How often did you see your friends or neighbors?" (iv) "How often did you make contact with your friends or neighbors by phone, email, or facsimile?" In the 2014 and 2017 surveys, participants were asked, "How often did you see or make contact with your family members or relatives who are living apart by phone, email, or facsimile?" Owing to limited survey items, we could not differentiate between face-to-face and non-face-to-face contact. The frequency of interaction was classified as follows: (i) 6–7 times a week (almost every day); (ii) 4–5 times a week; (iii) 2–3 times a week; (iv) once a week; (v) 2–3 times a month; (vi) once a month; (vii) less than once a month; (viii) none (scored as 0 [none] to 7 [almost every day]). The total score of face-to-face or non-face-to-face contact with non-resident family members and friends was used as the social interaction score (score range: 0–14). This social interaction score was defined originally in this study; however, the items of the social interaction measure were common to those used in previous studies (5, 9, 22). Since individuals in these previous studies and several other studies (22–24) were considered to be socially isolated if they made contact less than once per week, we believed that it is reasonable to set the corresponding 4 points as the cutoff for social isolation.

TABLE 1 Time, participants, and response rate of each mail survey.

Wave	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5	Wave 6	Wave 7
Time (year)	2012	2013	2014	2017	2018	2019	2020
Participants	Residents aged 65–85 who lived in survey areas	Residents aged 65–86 who lived in survey areas	Residents aged 65–87 who lived in survey areas	Past respondents and new participants aged 65 years	Past respondents and new participants aged 65 years	Past respondents and new participants aged 65 years	Past respondents and new participants aged 65 years
Sent (*n*)	7,015	7,128	7,737	4,215	4,267	3,745	3,289
Response (*n*)	3,696	3,656	3,522	2,738	2,594	2,395	2,118
Response rate (%)	52.7	51.3	45.5	65.0	60.8	64.0	64.4

2.3. Mortality

Information regarding mortality was obtained from October 1, 2012, to November 1, 2020, from the database administrated by the ward office. This mortality information was informed by the notification of death forms for residents.

2.4. Covariates

Age, sex, chronic diseases (i.e., hypertension, diabetes mellitus, stroke, and heart disease), instrumental activities of daily living (IADL), self-rated health, perceived financial status, living alone status, and social participation are associated with social isolation (1). In the current study, these factors were included as covariates in the analyses. We used covariate data from the year in which each participant first responded to the survey.

Age and IADL were entered as continuous variables and others as categorical variables. For chronic diseases, the presence or absence of each disease was entered individually. The question regarding self-rated health provided four choices: very healthy, healthy enough, not very healthy, and not healthy. The IADL score was assessed using a subscale of the Tokyo Metropolitan Institute of Gerontology Index of Competence, which includes five questions on instrumental self-maintenance (25). The question regarding perceived financial status was evaluated using five options: very comfortable, slightly comfortable, neither comfortable nor hard, a little hard, and very hard.

Social participation was examined in five activity groups: neighborhood associations, senior citizen clubs, hobby groups, sports groups, and volunteer groups (26).

2.5. Statistical analyses

Participants' baseline characteristics are presented as means and standard deviations (SDs) for continuous variables and as percentages for categorical variables. The aging trajectories of the social interaction score were identified by group-based semiparametric mixture modeling (19) using TRAJ in STATA 15.1 (StataCorp LLC; College Station, Texas, United States). We used a censored normal (cnorm) model to identify the aging trajectories. The number of groups was examined for 2, 3, and 4 with cubic curve models; the best-fitting model was selected by comparing the Bayesian information criterion values. Sex-stratified analysis was also conducted for the aging trajectories of the social interaction score.

To identify factors associated with the aging trajectory patterns of social interaction, multiple logistic regression analyses were conducted. The dependent variable was the trajectory patterns, and explanatory variables were the baseline data on sex, age, self-rated health, living alone status, perceived financial status, chronic disease, social participation, and IADL score.

The association between aging trajectory patterns of social interaction and all-cause mortality was investigated using Cox proportional hazards models, which started from the baseline survey for each participant until death or the end of follow-up (November 1, 2020), while adjusting for sex, age, chronic disease, living alone, and IADL score. The assumption that the proportional hazards remain constant over time was assessed based on the graphs on the cumulative survival curve. All statistical analyses, except for group-based trajectory modeling, were performed using SPSS version 27 (IBM Japan, Ltd.; Tokyo, Japan).

3. Results

This study analyzed data from 4,065 participants (2,216 women and 1849 men) with a mean age (SD) of 71.6 (±5.6) years (Table 2). The average duration of follow-up (SD) was 5.1 (±2.9) years, the average number of follow-up assessments was 4.2 (±1.9), and the total number of observations was 17,150. The average social interaction score (SD) was 7.5 (±3.5).

For the aging trajectories of social interaction scores, because two to four group models were examined, the two-group cubic trajectory model was identified as the best-fitting model based on the Bayesian information criterion values (Figure 1). Two trajectory patterns were observed: high-frequency and low-frequency groups (Figure 1). In the high-frequency group, the social interaction score for 65 years of age was approximately 10 points, and high-frequency contact almost every day was maintained until approximately 80 years of age. In contrast, in the low-frequency group, the social interaction score for 65 years of age was approximately 5 points, with a gradual decline in contact frequency. The score settled below 4 points, reaching the level of social isolation at approximately 80 years of age.

Similarly, two groups were identified by sex in a stratified analysis (Figure 2). Among men with high-frequency interaction, a rapid decrease in the frequency of social interaction was observed after 80 years of age. Conversely, among women, the frequency tended to remain the same, even after 80 years of age. The social interaction score among those aged 65 years in the low-frequency group was approximately 4 points for men and 6 points for women. Among men,

TABLE 2 Participants' baseline characteristics.

Variable	Men (*n* = 1849)		Women (*n* = 2,216)		All participants (*N* = 4,065)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	71.7	5.6	71.6	5.6	71.6	5.6
Chronic disease (%)						
Hypertension	42.0		38.7		40.2	
Diabetes mellitus	17.2		8.3		12.4	
Stroke	6.4		2.0		4.0	
Heart disease	16.1		7.9		11.7	
IADL score	4.7	0.8	4.9	0.6	4.8	0.7
Social interaction score	6.6	3.5	8.4	3.3	7.5	3.5
Self-rated health (%)						
Very healthy	11.3		11.2		11.2	
Healthy enough	68.3		69.4		68.9	
Not very healthy	15.3		14.8		15.0	
Not healthy	5.1		4.7		4.9	
Perceived financial status (%)						
Very comfortable	3.2		3.8		3.5	
A little comfortable	32.3		34.9		33.7	
Neither comfortable nor hard	39.1		41.6		40.4	
A little hard	20.7		16.0		18.1	
Very hard	4.7		3.8		4.2	
Living alone (%)	16.3		24.7		20.9	
Social participation (%)						
Neighborhood associations	26.2		26.9		26.6	
Senior citizen clubs	8.3		11.9		10.3	
Hobby groups	22.9		39.1		31.8	
Sports groups	18.7		26.2		22.8	
Volunteer groups	7.0		8.6		7.9	
Duration of follow-up (years)	4.9	2.9	5.3	2.8	5.1	2.9

SD, standard deviation; IADL, instrumental activities of daily living.

no decrease was observed; however, it tended to decline after 85 years of age among women.

Factors associated with the low-frequency group included male sex, younger age, no history of stroke, poor IADL score, poor self-rated health, poor perceived financial status, and poor social participation (Table 3). A stratified analysis by sex showed that the IADL score, perceived financial status, and social participation were associated with the trajectories of social interaction among men. Factors associated with such trajectories among women included hypertension, self-rated health, and social participation.

During the follow-up period, all-cause deaths occurred in 125 (6.0%) and 198 (9.9%) participants in the high- and low-frequency groups, respectively. The adjusted hazard ratio (HR) for all-cause mortality in the low-frequency group was 1.48 (95% confidence interval (CI): 1.16–1.88; Table 4). The stratified analysis by sex revealed a significant association and the adjusted HR was 1.72 (95% CI, 1.27–2.32) in men. The adjusted HR was 1.45 (95% CI, 0.98–2.14) in women, which was not significant.

4. Discussion

The present study identified the aging trajectories of social interaction scores using large-scale longitudinal data from a cohort of community-dwelling older adults and classified them into two groups. Overall, social interaction scores did not change rapidly with aging, even when divided into 3 or 4 groups. The high-frequency group showed a pattern where the social interaction score was 7 points or more, and interaction with others almost every day was maintained until over 80 years of age. Conversely, the low-frequency group had a score of approximately 5 points, indicating that they interacted with others 2–3 times a week at 65 years of age. The score dropped to less than 4 points at approximately 80 years of age, indicating that interaction occurred once a week. This study had over 4,000 participants, with an average follow-up duration of approximately 5 years, and it included more participants and a similar follow-up duration as compared to a previous study on aging trajectories (18).

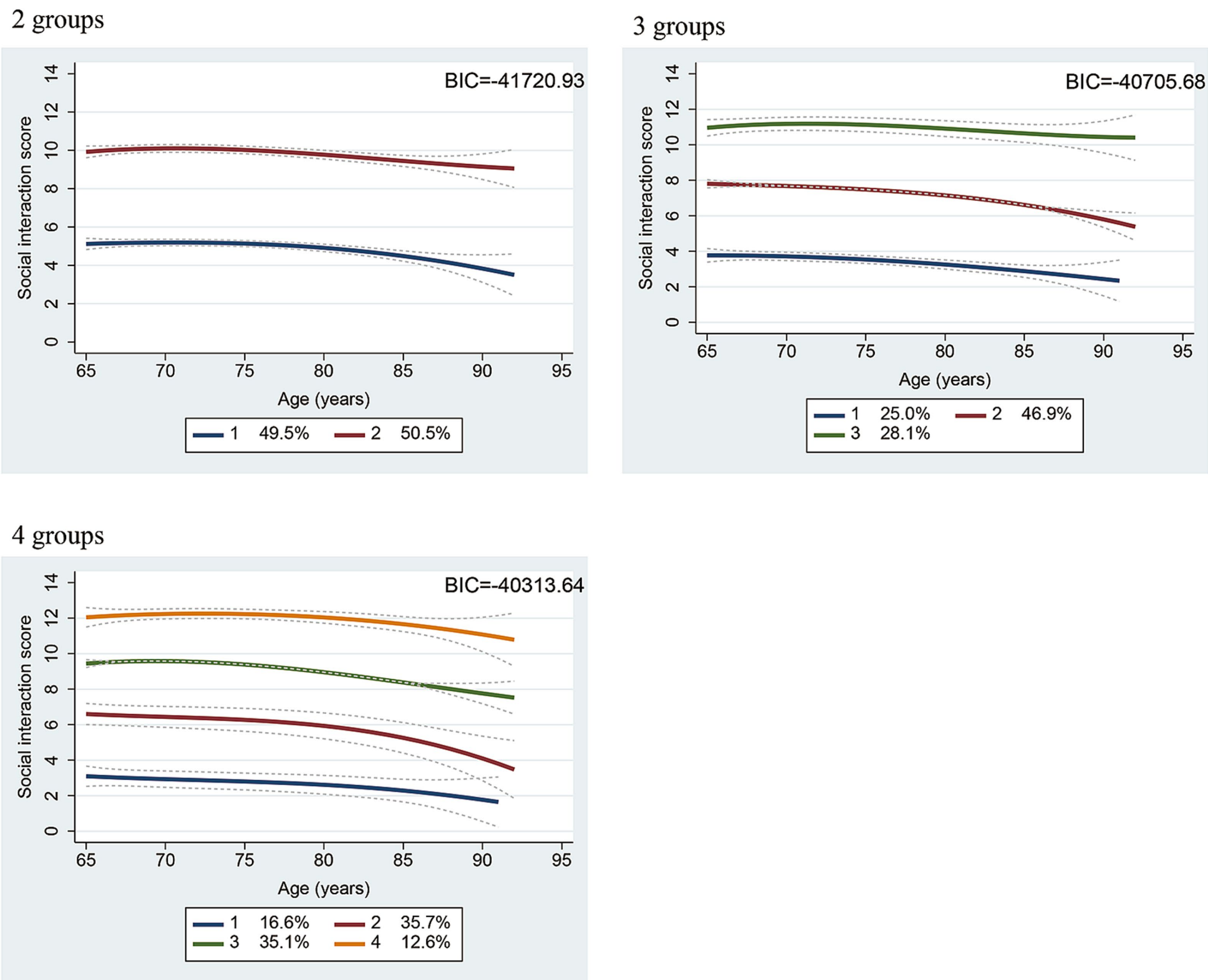

FIGURE 1
Two, three, and four trajectories for social interaction scores identified by a group-based semiparametric mixture model among all participants. BIC, Bayesian information criterion; Dotted line: 95% confidence interval.

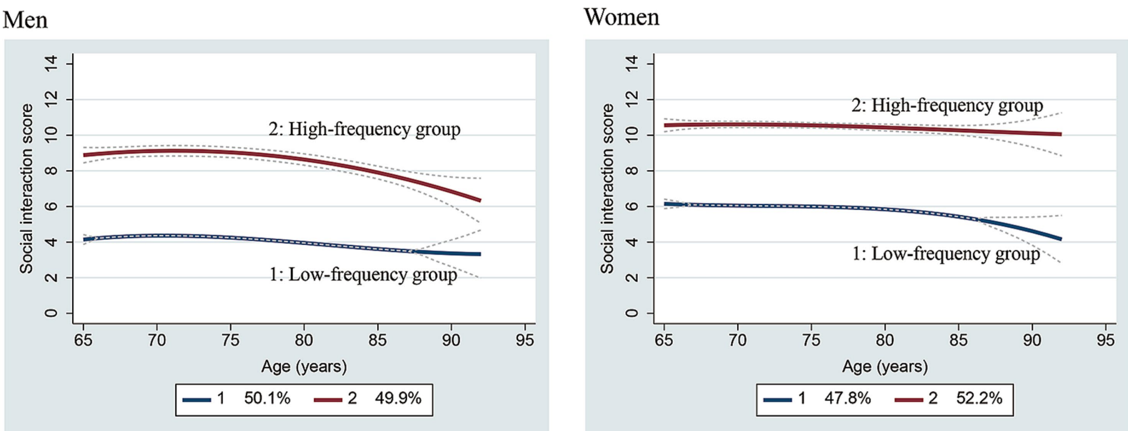

FIGURE 2
Two group trajectories for social interaction scores among men and women. Dotted line: 95% confidence interval.

Therefore, the trajectories of the social interaction scores identified in this study may better represent the trajectories of community-dwelling Japanese older adults.

Limited studies have reported the aging trajectories of variables concerning social interaction in older adults. These studies analyzed the aging trajectories of basic activities for daily living, physical

TABLE 3 Factors associated with the trajectory patterns for social interaction scores.

	Men		Women		All participants	
	OR	95% CI	OR	95% CI	OR	95% CI
Sex (reference: women)	–	–	–	–	**2.44**	2.10–2.82
Age (years) (1-year increments)	1.01	0.99–1.03	**0.98**	0.96–0.99	**0.98**	0.97–0.99
Chronic disease (reference: none)						
Hypertension	0.90	0.73–1.11	**0.81**	0.66–0.99	0.93	0.80–1.08
Diabetes mellitus	1.00	0.75–1.32	0.85	0.60–1.21	0.90	0.72–1.13
Stroke	0.74	0.47–1.17	0.74	0.36–1.52	**0.67**	0.46–0.97
Heart disease	1.18	0.89–1.58	0.76	0.53–1.10	1.07	0.85–1.34
IADL score (1-point increments)	**0.78**	0.67–0.92	0.86	0.71–1.04	**0.86**	0.77–0.97
Self-rated health (reference: very healthy)						
Healthy enough	1.40	0.99–1.98	**1.97**	1.41–2.75	**1.68**	1.32–2.14
Not very healthy	1.50	0.97–2.32	**2.55**	1.69–3.85	**2.17**	1.60–2.94
Not healthy	1.83	0.98–3.41	**4.67**	2.49–8.78	**2.74**	1.76–4.26
Perceived financial status (reference: very comfortable)						
A little comfortable	1.55	0.81–2.95	1.12	0.67–1.89	1.14	0.76–1.72
Neither comfortable nor hard	**2.08**	1.09–3.95	1.29	0.77–2.17	**1.51**	1.00–2.26
A little hard	**2.09**	1.08–4.06	1.30	0.75–2.25	**1.61**	1.05–2.46
Very hard	**3.40**	1.49–7.75	1.65	0.80–3.41	**2.36**	1.36–4.08
Living alone (reference: not living alone)	1.30	0.97–1.74	0.84	0.68–1.05	0.99	0.82–1.18
Social participation (reference: participation)						
Neighborhood associations	**1.88**	1.47–2.41	**1.37**	1.10–1.72	**1.68**	1.42–1.99
Senior citizen clubs	1.49	0.99–2.25	0.91	0.66–1.25	1.08	0.84–1.40
Hobby groups	**2.09**	1.61–2.72	**1.81**	1.47–2.22	**1.71**	1.45–2.01
Sports groups	**2.02**	1.52–2.69	**1.50**	1.20–1.88	**1.57**	1.31–1.87
Volunteer groups	1.21	0.79–1.86	1.24	0.87–1.78	**1.57**	1.18–2.09

CI, confidence interval; OR, odds ratio; IADL, instrumental activities of daily living; numbers in bold are statistically significant; dependent variable: pattern of trajectories for social interaction score (reference: high-frequency group).

performance such as grip strength and walking speed (17), and higher-level functional capacity (18) and reported patterns where function declined rapidly with age. Thus, we deduced that social interaction also followed patterns in which interaction declined rapidly. However, those patterns were not found in the present study, suggesting that individuals exposed to an increased frequency of social interaction can maintain the level of social interaction, even if their physical function declines. The present study found that people have stable levels of social interaction throughout their later life. In a longitudinal study on age-related changes in social network size, social network size was maintained from 57 to 73 years of age (20). Therefore, to prevent social isolation, measures to ensure high-frequency social interaction are needed from a young age. It is important to promote social interaction from a young age, not just in old age. Social interaction should continue to be encouraged even as health, lifestyle, and work environment change with age. It is necessary to disseminate this information and provide opportunities for maintaining social interaction.

The sex-stratified analysis showed that the frequency of social interaction was maintained among the high-frequency group of women, even at a later age. Conversely, a gradual decline was observed among men over 75 years, followed by a rapid decline after the age of 80. The social interaction score among women aged 65 years in the low-frequency group was 6 points, which corresponds to an interaction frequency of 4–5 times a week; however, after 85 years of age, it declined to 4 points, which corresponds to possible social isolation. The score was 4 points for men, which was deemed as indicative of social isolation (5). As there are sex-related differences in social participation (27) and the association between social isolation and functional decline (21), sex-related differences in functional status and communication style could affect social interaction in later life. This study found sex-related differences in the trajectory of social interaction frequency leading to isolation. Recent studies reported that the coronavirus disease pandemic significantly increased social isolation among older adults (28–30); particularly, men aged ≥50 years experienced the greatest increase in the prevalence of social isolation (23). Thus, men in the low-frequency group must be screened at an early age and provided with timely interventions (e.g., when they are middle-aged). Many men may change their lifestyle and work environment owing to retirement in middle age. Therefore, it is necessary to share information about the importance

TABLE 4 Independent associations of social interaction trajectories with all-cause mortality.

Social interaction trajectory	Incident all-cause deaths		All-cause mortality	
			Crude	Adjusted
	n	%	HR (95% CI)	HR (95% CI)
All participants				
High-frequency group	125	6.0	1	1
(*n* = 2070; 50.9%)				
Low-frequency group	198	9.9	1.72	1.48
(*n* = 1995; 49.1%)			(1.37–2.15)	(1.16–1.88)
Men				
High-frequency group	72	7.9	1	1
(*n* = 915; 49.5%)				
Low-frequency group	131	14.0	1.89	1.72
(*n* = 934; 50.5%)			(1.42–2.52)	(1.27–2.32)
Women				
High-frequency group	52	4.4	1	1
(*n* = 1,174; 53.0%)				
Low-frequency group	68	6.5	1.52	1.45
(*n* = 1,042; 47.0%)			(1.06–2.19)	(0.98–2.14)

CI, confidence interval; HR, hazard ratio; numbers in bold are statistically significant; Cox hazards regression models adjusted for sex, age, chronic diseases, instrumental activities of daily living score, and living alone.

of social interaction before reaching the age of 65 years. In women, decreased social interaction was seen in the low-frequency group over the age of 85 years, which could be attributed to decreased walking ability and muscle strength in older age. Encouraging exercise to maintain walking ability and muscle strength may prove effective for women in the low-frequency group.

In this study, male sex, younger age, no history of stroke, lower IADL scores, poor self-rated health, poor perceived financial status, and poor social participation were associated with the low-frequency group of trajectories. These factors are consistent with a previous study that examined factors of social isolation (1). Since the social interaction score in the low-frequency group in the present study was between 3 and 5 points, indicating an interaction frequency of 2–3 times a month to 2–3 times a week, the factors of the low-frequency group could be consistent with the previous study (1), where a social interaction frequency of less than once a week was defined as social isolation.

The factors associated with the trajectory patterns of social interaction among men and women varied. Self-rated health in women alone and perceived financial status in men alone were sex-specific factors affecting the trajectory pattern, suggesting that social interaction is restricted by women's health and men's financial status. Women face a higher risk of declining mobility than men (31), which could result in poor self-rated health, thus restricting social interaction. For men, work may be the main opportunity for social interaction; not working for an income may lead to reduced social interaction. There was no significant difference between the low-frequency and high-frequency groups for both men and women, suggesting that living alone was not an independent factor of social interaction. This result is in line with a previous study that showed that a poor social network rather than living alone was associated with adverse health outcomes (32). Indicating whether or not people live alone is not an issue of social isolation.

The adjusted HR to all-cause mortality in the low-frequency group of trajectories in social interaction was 1.48, similar to the random effect weighted average OR for 1.40 (95% CI: 1.06–1.86) in a meta-analysis of mortality owing to social isolation (6). Thus, the results suggest that the low-frequency group faces a similar risk of death to those associated with social isolation. A study examining the association between the co-existence of social isolation and homebound status, with a risk of all-cause mortality through a six-year follow-up in Japanese older adults (24), found that the adjusted HR to all-cause mortality in the group of social isolation coexisting with being homebound was 2.19 (95% CI: 1.04–4.63), which was higher than that in the current study. The risk of mortality further increased when the homebound group overlapped with the low-frequency group of the social interaction trajectory pattern.

Among men, the adjusted HR for all-cause mortality in the low-frequency group was 1.72, which was higher than that in the overall analysis, suggesting that men in the low-frequency group had a particularly high risk of mortality. As described above, this could be because this group of men is already socially isolated at 65 years. Meanwhile, among women, the association between the low-frequency group and mortality was not significant in the adjusted model. This study showed that in the low-frequency group, men had a higher risk of all-cause mortality than women.

This study is the first to identify the aging trajectories of social interaction scores in Japanese older adults using large-scale longitudinal data. Particularly, men in the low-frequency group are already socially isolated from 65 years and face a higher risk of mortality. This study suggests that early interventions (e.g., beginning in middle age) are important for men in the low-frequency group. The factors associated with men in this group were low IADL, low perceived financial status, and no participation in neighborhood associations, hobby groups, and sports groups. It is important to provide exercises that improve the walking ability to maintain IADL (33). A multicomponent intervention, comprising physical, social, health education, and environmental interventions, are suggested to be effective for promoting social participation (34). Providing the information and opportunity on those interventions from middle adulthood is important. In addition, since this study showed that perceived financial status in men is one of the factors of the low-frequency group, the risk of social isolation may reduce in men by providing employment opportunities.

This study has a few limitations. First, it was conducted in an urban area in Japan. The aging trajectories of social interaction in rural areas and other countries may vary; thus, the findings may not be adequately representative of these populations. Future studies in other regions are necessary. As this study involved a mail survey, marital status, physical activity, smoking, diet, and BMI could not be examined due to limited survey items. In addition, other potential confounders, such as social support from or relationships with family members and severe illness (e.g., cancer), could not be examined. Further, we uniquely defined the social interaction score to assess the degree of social interaction. However, the items used to calculate the score were the same as those used for assessing social interaction in the previous studies (5, 22). We believe that the degree of social isolation was quantitatively evaluated in this study. Moreover, trajectories associated with other social variables, such as social networks, must be identified (8). Although IADL may change over time, we did not treat it as a time-dependent covariate in the Cox hazards model since most of the participants in this study had independent IADL, and the change over time was assumed to be small. Further, we did not examine the risk associated with the cause of death because the incidence of mortality was not high. However, some studies have reported that social isolation can increase the risk of cardiovascular disease (3, 35). Future studies should explore the risk of aging trajectory patterns in social interaction with a focus on the cause of death.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics committee of the Tokyo Metropolitan Institute of Gerontology. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HKa and SO contributed to the design and concept of the study. HKa, ME, KIt, YF, KIh, HH, HKi, and SO acquired the data. HKa, ME, and KIt analyzed and interpreted the data as well as drafted the manuscript. YF, HS, and SO revised the manuscript for important intellectual content. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Education is power: preserving cognition in the UK biobank

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Introduction: Dementia is a debilitating syndrome characterized by the gradual loss of memory and cognitive function. Although there are currently limited, largely symptomatic treatments for the diseases that can lead to dementia, its onset may be prevented by identifying and modifying relevant life style risk factors. Commonly described modifiable risk factors include diet, physical inactivity, and educational attainment. Importantly, however, to maximize the utility of our understanding of these risk factors, tangible and meaningful changes to policy must also be addressed.

Objectives: Here, we aim to identify the mechanism(s) by which educational attainment influences cognition.

Methods: We investigated data from 502,357 individuals (M_{age}=56.53, SD_{age}=8.09, 54.40% female) from the UK Biobank cohort via Structural Equation Modelling to illustrate links between predictor variables (i.e., Townsend Deprivation Index, coastal distance, greenspace, years of education), covariates (i.e., participant age) and cognitive function as outcome variables (i.e., pairs-matching, trail-making task B, fluid intelligence).

Results: Our model demonstrated that higher education was associated with better cognitive performance (ps < 0.001), and this relationship was mediated by indices of deprivation, and coastal distance.

Conclusion: Accordingly, our model evinces the mediating effect of socioeconomic and environmental factors on the relationship between years of education and cognitive function. These results further demonstrate the utility and necessity of adapting public policy to encourage equitable access to education and other supports in deprived areas.

KEYWORDS

education, cognition, socioeconomic status, greenspace, coastal distance

1. Introduction

Dementia characterizes a debilitating syndrome involving cognitive decline and loss of memory severe enough to hamper independent, daily functioning (1). Globally, dementia is a leading cause of death and imparts immense economic, societal and personal burdens (2), with currently limited treatment options available. Moreover, as the global population ages beyond 65 years, the incidence of dementia cases is expected to surpass 152 million by the year 2050 (3), and the need to find means to prevent, diagnose and treat dementia becomes even more pressing. Assessing, understanding, and modifying dementia risk factors which precipitate disease onset is a critical step in prevention. Risk factors include poor diet, smoking and alcohol consumption, physical inactivity, depression and lack of education; in combination, these factors may contribute to up to 40% of known dementias (4). In order to maximize the management of relevant risk factors, tangible and meaningful changes to policy must be implemented to support personal mitigation efforts. For example, policies need to narrow the gap between socioeconomic classes to reduce undue stress and improve mental health (5, 6). Providing more equitable access to education for those living in underserviced/impoverished communities is one way to achieve this.

Education is one important modifiable risk factor and evidence suggests that disparities in access to education can encumber disadvantaged individuals. In developed countries, educational attainment has long been presumed to be associated with improved physical (7) and mental health (8), and is highly related to one's employability, income, and overall individual adulthood socioeconomic status (SES). Children belonging to low SES groups are less likely to develop fundamental reading skills (9), have a lower level of baseline cognitive performance (10, 11), are less likely to have access to learning materials in the home (12), and are more likely to accrue higher-than-average student dept. (13). This combination of factors hinders their ability to be educated to the same degree as high-SES individuals, and may lower their chances of improving their SES in the future; perpetuating the cycle of inequality. Interestingly, the literature regarding the *protective* benefits of education on cognition is mixed depending on whether the focus is on the level or change in cognition (14). That is, higher education has been shown to have no effect on the speed of cognitive decay due to normal aging in some populations (15), whereas Fletcher and colleagues (16) demonstrated that in genotyped siblings, higher educational attainment was associated with higher cognitive scores. The protective benefits seen in the latter may be attributed to higher cognitive reserve accrued, as a result of more education (17, 18). Accordingly, the literature outlined above provides evidence for the need for more equitable access to education and the benefits education may have on one's cognitive status, as well as one's mental and physical health.

Moreover, the environment in which individuals live and work influences individuals' health status. Built environment includes factors such as housing structure and architecture, environmental quality, walkability and green/blue space (19), as well as measures of population density and pollution (20), which differs between urban and more natural rural/coastal environments. Previous research has identified that a higher percentage of greenness is associated with lower risks of psychological distress (19), promotes active daily living, reduces active stress levels, and provides areas for therapeutic healing (21). Indeed, recent research has found that individuals living in greener environments have been found to be less likely to suffer from depression (22) and possess better cardiovascular health (23). Previous work has also proposed that children who live in greener environments are more likely to possess more highly developed cognitive functions (24). However, other work does not support this finding, and suggests that greenspace neither protects nor promotes cognitive development (25) or mental health (26). With regards to coastal distance, the literature is again varied. Similar to those investigations exploring greenspace, Gascon et al. (27) present evidence suggesting there is a positive association between living close to water and improved mental health, well-being, and an increased likelihood of engaging in physical activity. Nutsford et al. (28) also provide evidence that available blue space (e.g., being closer to a coastline) facilitates social interaction and acts to preserve mental health via inherent therapeutic properties. In contrast, in some populations the proximity to water can have negative effects on mental health outcomes. Helbich et al. (29) demonstrated that although living close to inland blue spaces imparted a protective benefit to the mental health of a Dutch cohort of 105,398 individuals, living nearer to a coastline had the opposite effect. Indeed, women, but not men, who lived closer to the Dutch coastline were more likely to commit suicide than those living inland.

The studies included above are a collection of reviews (9, 14, 17, 18, 27), and primary cross-sectional and longitudinal analyses which make use of linear, logistic, multi-level, genomic, and/or structural equation modelling techniques to describe large cohort data (7, 8, 10–13, 15, 16, 19–26, 28, 29). Taken together, the current body of literature provides only mixed results for how education, individual-specific deprivation (i.e., separate contributors of SES), and built environment interact to support or hinder cognitive and mental health outcomes. Moreover, very little has been done in terms of explicitly assessing potential direct and indirect links between these aforementioned variables. That is, the potential mechanism(s) regarding how educational attainment may influence cognitive function via measures of deprivation and built environment is as yet un-examined. To our knowledge, the following investigation is the first to examine this relationship using data from the UK Biobank cohort. We hypothesized that education would have positive effects on cognition; however, this relationship would be better explained by some mediation via metrics of deprivation and built environment.

2. Materials and methods

2.1. Participants

Data from 502,357 individuals ($M_{age} = 56.53$, $SD_{age} = 8.09$) from the UK Biobank cohort (30) were included in this project (see Table 1 for more detail). The UK Biobank study received ethical approval from

TABLE 1 Participant characteristics, cognitive performance, SES, and built environment.

Characteristics	N		
Age	502,357	*M* (SD)	56.53 (8.09)
Sex	502,360	% Female	54.40%
Education	495,642	*M* (SD)	18.11 (2.77)
Cognitive function			
Fluid Intelligence	123,579	M(SD)	6.41(2.06)
Trail-making task-B	103,998	M(SD)	66.81(25.75)
Pairs-matching task	118,495	M(SD)	4.20(3.12)
Deprivation			
Townsend deprivation index	501,734	M(SD)	−1.29(3.09)
Built environment			
Coastal distance (km)	497,397	M(SD)	41.64(27.71)
Percentage greenspace	440,736	M(SD)	35.27(23.22)

Uncorrected group means and standard deviations [*M*(*SD*)] for age (in years), years of education, Townsend Deprivation Index score, percentage of greenspace, coastal distance, fluid intelligence score, trail-making task-B duration, and number of incorrect pairs-matching trials. Note that we also present the % of females in our sample (*N*).

the UK Biobank Research Ethics Committee (approval letter dated 17, June 2011: Ref 11/NW/0382) and was conducted in accordance with the Declaration of Helsinki. All participants gave informed, written consent.

2.2. Predictor variables

2.2.1. Built environment, deprivation, and education

Our analyses included three predictor variables: built environment, deprivation and education. Built environment was estimated by participants' distance to the coastline and the percentage of greenspace around where they lived. The Townsend Deprivation Index (TDI) was used to quantify individual levels of deprivation. The TDI variable used here is a standardized individual rating of deprivation which in and of itself reflects one's "real" living conditions according to geographic constraints and not simply a rating of poverty (31). The TDI incorporates common measures normally used as a proxy of SES such as of unemployment, car-ownership, home-ownership and home overcrowding, but excludes education (31). Higher values on this index indicate higher levels of deprivation and lower SES. Finally, years of education was separately calculated via an algorithm which imputed years of education to the missing values of the "age completed full time education" variable based on the "qualifications" variable. The inclusion of both TDI and education-related variables allows us to understand the degree to which these components commonly assumed to contribute to SES influence each other and cognitive function. Participant age was included in our analysis as a co-variate. These data were collected between 2006 and 2010.

2.3. Outcome variables

2.3.1. Cognitive function

Cognitive function was estimated via three separate tests: the 6-pair pairs-matching test (PM6), the trail making task-B (TMTB), and an examination of fluid intelligence (FI). These tests assessed various aspects of cognition including memory, executive function, and abstract reasoning, respectively (see UK Biobank data showcase for more detail; https://biobank.ndph.ox.ac.uk/showcase/) and were included due to their sensitivity to cognitive decline/disruption over the lifespan (32). The cognitive variables used here are comprised of data taken between 2014 and 2015 and therefore the volume of collected data may differ from predictor variables according to rates of attrition.

2.4. Statistical analyses

2.4.1. Pre-processing

Data were pre-processed and analyzed using Stata SE 17.0 via the Dementias Platform UK (DPUK) Data Portal (33). Participants aged 40–73 were included in our analyses. This relatively large age-range was retained in order to assess the validity of a model which predicts cognitive function across time, rather than in an age-range in which dementia typically occurs (i.e., 60–70 years) (1). We assessed the normality of our variables of interest (see below) and where appropriate, skewed (i.e., $g_1 > 1.0$) data were log-transformed for normalisation.

2.4.2. Spearman correlations

We employed Spearman correlations on our data to explore associations between measures of deprivation, coastal distance, greenspace, the number of incorrect responses on the PM6, the duration of an alphanumeric path in the TMTB, total FI scores, years of education and age (Table 2). Correlations were Bonferroni corrected and associations were considered significant if $p < 0.01$.

2.4.3. Structural equation model

We employed a structural equation model (SEM) to assess direct and indirect effects between education, deprivation and built environment on cognition. That is, we aimed to create a single model to assess a possible mechanistic pathway by which our predictor variables may influence cognitive outcomes. Prior to creating our model, simple regressions of the variables of interest were performed to better inform direct and indirect model paths. Our model was estimated using a maximum likelihood with missing values (MLMV) test and we report standardized coefficients and beta values. The MLMV method assumes joint normality and, if present, randomly occurring missing values. The resulting model contains the following variables.

Cognitive function included incorrect PM6 responses (variable: 20132), the time required to complete the TMTB alphanumeric path (variable: 20157), and a score of FI (variable: 20191). Cognitive variables were allowed to covary. We chose to not represent these variables in a latent construct in order to assess the differential effects of our predictor variables on various aspects of cognition. Predictor variables included education, deprivation, and built environment which were represented by imputed years of education, scores on the TDI (variable: 22189), the distance to the coastline in kilometers (Coast; variable: 24508) and the percentage of greenspace within a 300 m buffer area (Green; variable: 24503), respectively. The three latter variables were connected via covariance links to assess their relationship. As the direction of any association between these variables cannot be confirmed here, we chose to omit direct path links between them. Age (a continuous variable; variable: 21022) was also entered into our SEM to control for any confounds and was linked to Education via a covariance link (Figure 1). Due to the large sample size, effects were deemed significant when $p < 0.01$ (34). For ease of replication, we have included our STATA script in the Supplementary material of this work.

3. Results

3.1. Participant characteristics

Our sample was on average 56.53 (SD = 8.09) years of age, comprised of mostly females (54.4%) and had completed a mean of 18.11 (SD = 2.77) years of education (Table 1).

3.2. Spearman correlations

Our results indicated that years of education was correlated to all cognitive variables (rs > −0.04, ps < 0.001). TDI scores correlated with

TABLE 2 Correlation matrix for participant cognitive variables.

	Age	Education	TDI	Coast	Green	PM6	TMTB	FI
Age	–	–	–	–	–	–	–	–
Education	−0.13⁑	–	–	–	–	–	–	–
TDI	−0.10⁑	0.002	–	–	–	–	–	–
Coast	0.01	0.02⁑	−0.06⁑	–	–	–	–	–
Green	0.05⁑	−0.06⁑	−0.30⁑	0.05⁑	–	–	–	–
PM6	0.14⁑	−0.04⁑	−0.002	0.01	−0.001	–	–	–
TMTB	0.38⁑	−0.22⁑	0.02⁑	−0.01⁑	0.01	0.18⁑	–	–
FI	−0.10⁑	0.33⁑	−0.03⁑	0.01*	−0.02⁑	−0.12⁑	−0.42⁑	–

Correlation matrix *r* values for all variables of interest with Bonferroni corrected significance levels. TDI, Townsend Deprivation Index; PM6, 6-pair pairs-matching task; TMTB, trail-making task-B; FI, fluid intelligence. Associations marked with * indicate $p < 0.01$; those marked with ⁑ indicate $p < 0.001$. $N = 88{,}436$.

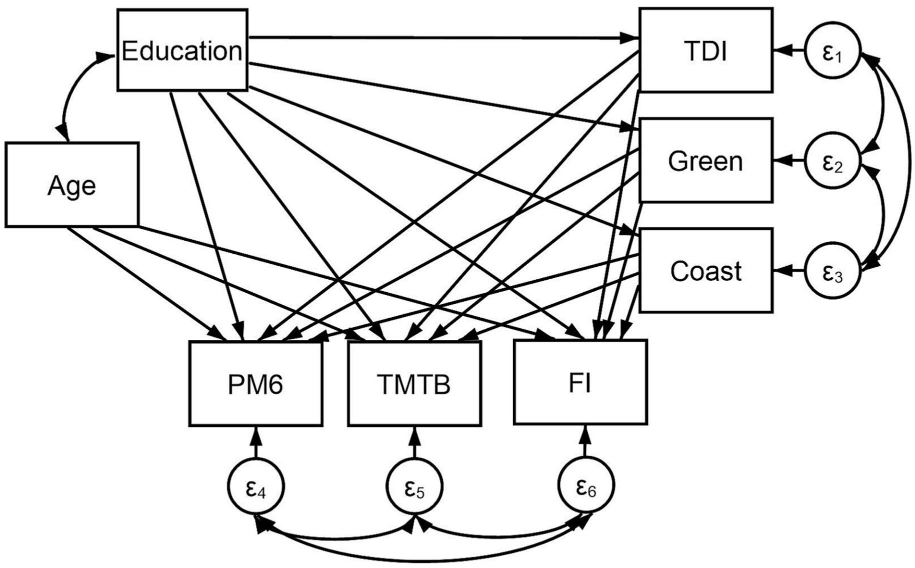

FIGURE 1
Structural equation model including predictor variables: Education (i.e., imputed years of education), TDI (i.e., Townsend Deprivation Index total score; variable: 22189), Coast (i.e., the distance to the coastline in kilometers; variable: 24508) and Green (i.e., percentage of greenspace within a 300 m buffer area; variable: 24503); and mediator variable: Age (variable: 21022). Paths extend from these variables to three cognitive variables: PM6 (i.e., number of incorrect responses on the pairs-matching task; variable: 20132), TMTB (i.e., the time required to complete the trail-making task-B alphanumeric path; variable: 20157), and FI (i.e., fluid intelligence score; variable: 20191). Covariance links join Age and Education; FI, TMTB, and PM6; and TDI, Green, and Coast. *N* = 502,357.

TMTB times ($r = 0.02$, $p < 0.001$) and with FI ($r = -0.03$, $p < 0.001$), whereas coastal distance and greenspace were correlated only to TMTB times ($r = -0.01$, $p < 0.001$) and FI ($r = -0.02$, $p < 0.001$), respectively. We note also that all the cognitive variables used were correlated to each other (rs > −0.12, ps < 0.001), as were TDI, greenspace and coastal distance (rs > 0.05, *ps* < 0.001). Finally, years of education was correlated to all the variables included in our model (rs > 0.02, ps < 0.001) except TDI (r = 0.002, *p* > 0.99). A full correlation matrix is presented in Table 2.

3.3. Structural equation model

3.3.1. Regression paths

Figure 1 demonstrates direct paths extending from each predictor variable (i.e., Education, TDI, Coast, Green) and Age to the cognitive outcome variables (i.e., PM6, TMTB, and FI). Direct links were also included between Education and TDI, Coast, and Green to assess the mediation of the putative relationships between education and various cognitive domains.

3.3.2. Estimation and fit

The model fit was deemed "good" according to accepted standards [e.g., (35)]. The root mean squared error of approximation (RMSEA: differences between predicted and observed outcomes) = 0.06, and the comparative fit index (CFI: metric of the model's improvement from baseline to proposed iterations) = 0.94.

Figure 2 demonstrates only statistically significant path links within our model. In particular, lower education was associated with higher deprivation ($\beta = -0.07$, $p < 0.001$), living closer to the coast ($\beta = 0.01$, $p < 0.001$) and inhabiting an area with more greenspace ($\beta = -0.01$, $p < 0.001$). The covariance links between

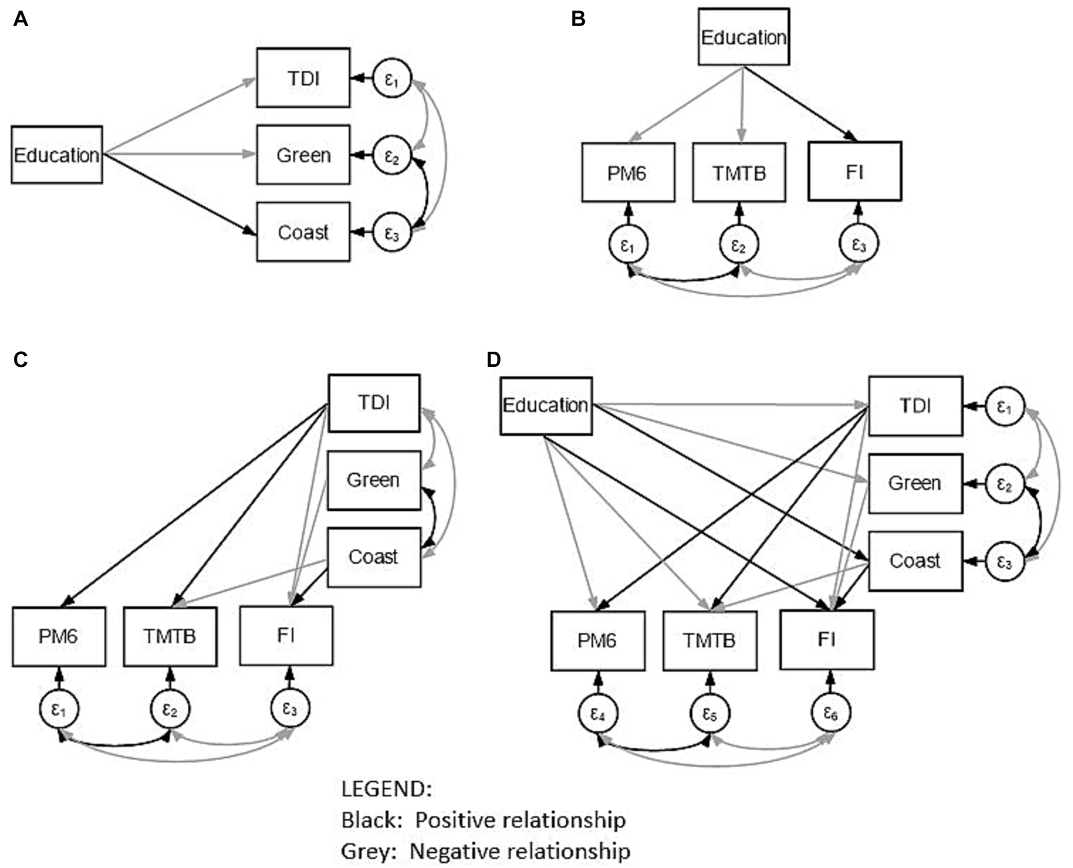

FIGURE 2
A simplified illustration of our model (D) as well as individual panels illustrating direct and indirect links between predictor and outcome variables as well as covariance links: education and the Townsend Deprivation Index (TDI), greenspace (Green), and coastal distance (Coast) **(A)**; education and scores on the pairs-matching task (PM6), the trail-making task B (TMTB) and fluid intelligence (FI) **(B)**; and Townsend Deprivation Index, greenspace and coastal distance with scores on the pairs-matching task, the trail-making task B and fluid intelligence are also included **(C)**. Note that only statistically significant positive (black arrows) and negative (gray arrows) interactions are presented. The covariate of Age is not included for ease of visualization.

TDI, coastal distance and greenspace were also statistically significant ($\beta > 0.03$, $p < 0.001$) indicating that higher deprivation was associated with living closer to the coast and in greener areas. Moreover, higher education was shown to predict better performance on the PM6 ($\beta = -0.02$, $p < 0.001$) and TMTB ($\beta = -0.17$, $p < 0.001$), and higher FI ($\beta = 0.32$, $p < 0.001$). Lower deprivation was related to fewer incorrect PM6 responses ($\beta = 0.01$, $p < 0.001$), shorter TMTB times ($\beta = 0.08$, $p < 0.001$) and greater FI ($\beta = -0.06$, $p < 0.001$). Living closer to the coastline was associated with longer TMTB times ($\beta = -0.01$, $p < 0.001$) and lower FI ($\beta = 0.01$, $p = 0.003$); inhabiting an area with less greenspace was related only to higher FI ($\beta = -0.01$, $p < 0.001$). Results demonstrated a partial mediation of the effect of education on cognitive performance by measures of deprivation and built environment. Indeed, β values for PM6, TMTB and FI were attenuated from (−0.07) to (0.01, 0.08, and − 0.06) by TDI. We also see attenuation of β values of the relationship between education and TMBT and FI from (0.01) to (−0.01 and − 0.01, respectively) by coastal distance. Greenspace was not shown to mediate the relationship between education and cognition. Finally, older age was associated with poorer performance on all cognitive variables ($\beta s > -0.09$, $ps < 0.001$). See Table 3 for the full SEM output.

4. Discussion

We sought to explore how education, deprivation and built environment influence cognition in a middle-aged cohort using UK Biobank. The following sections will discuss the links between age and cognition, as well as how education's influence on various domains of cognition is mediated by measures of deprivation and built environment.

4.1. Deprivation and coastal distance mediate the relationship between education and cognitive function

Education is one of the single most important modifiable determinants of health which predicts employment, income, overall SES and well-being (36). Our model demonstrates that higher educational attainment was found to be positively associated with improved cognitive performance. We provide evidence for the association between higher education and fewer incorrect PM6 responses, shorter TMTB durations, and better FI. As expected, these associations were all found to be mediated by individual deprivation

TABLE 3 Structural equation model output.

	Predictor	β	SE	z	p	95% CI	
TDI							
	Education	−0.07	0.001	−51.22	<0.001*	−0.076	−0.070
Coast							
	Education	0.01	0.001	9.15	<0.001*	0.01	0.016
Green							
	Education	−0.01	0.002	−5.23	<0.001*	−0.011	−0.005
PM6							
	TDI	0.01	0.003	3.64	<0.001*	0.006	0.019
	Coast	0.006	0.003	1.99	0.046	0.0001	0.012
	Green	−0.002	0.003	−0.53	0.600	−0.008	0.004
	Age	0.13	0.003	43.09	<0.001*	0.124	0.136
	Education	−0.02	0.003	−5.35	<0.001*	−0.023	−0.011
TMTB							
	TDI	0.08	0.003	24.97	<0.001*	0.072	0.084
	Coast	−0.01	0.003	−5.31	<0.001*	−0.020	−0.009
	Green	0.002	0.003	0.70	0.485	−0.004	0.008
	Age	0.38	0.003	147.44	<0.001*	0.376	0.387
	Education	−0.17	0.003	−58.59	<0.001*	−0.178	−0.166
FI							
	TDI	−0.06	0.003	−21.25	<0.001*	−0.071	−0.059
	Coast	0.01	0.003	2.99	0.003*	0.003	0.013
	Green	−0.01	0.003	−4.27	<0.001*	−0.018	−0.007
	Age	−0.09	0.003	−30.48	<0.001*	−0.091	−0.080
	Education	0.32	0.003	117.56	<0.001*	0.312	0.323

The left most column indicates the variables of interest and include: TDI (i.e., Townsend Deprivation Index), Coast (i.e., the distance to the coastline in kilometers), Green (i.e., percentage of greenspace within a 300 m buffer area), PM6 (i.e., number of incorrect responses on the 6-pair pairs-matching task), TMTB (i.e., the time required to complete the trail-making task-B alphanumeric path) and FI (i.e., fluid intelligence score). Predictor variables indicate those which have direct paths to the variable of interest. The output provides standardized beta (β) values, standard error (*SE*), *z* scores, *p* values, and 95% confidence intervals (95% CI). For ease of interpretation, *p* values marked with * indicate a statistically reliable association: $p < 0.01$. $N = 502{,}357$.

levels; however, our model also demonstrated that built environment factors commonly assumed to impart positive health benefits (26, 27) had the opposite effect. Here, the proximity to a coastline did not predict PM6 performance. In contrast, living closer to the coastline was related to longer TMTB durations and worse FI. Similarly, although greenspace percentage was not related to either PM6 or TMTB task performance, living in an area with more greenspace was related to worse FI. We will address these points in turn and will then provide some examples of prospective policy changes which warrant further investigation.

First, in addressing the positive relationship between education and cognition, a parsimonious explanation of our results can be provided via the cognitive reserve hypothesis (27). Cognitive reserve has been proposed to be an amalgamation of individual differences in cognitive processing which allows for one to better cope with normal and/or abnormal processes of aging. For example, higher cognitive reserve has been thought to slow the onset of cognitive decline (18). Indeed, higher levels of education are associated with more cognitive stimulation, as well as better income and more stable work environments commonly associated with higher SES. As well, the combination of more education and the greater opportunities afforded individuals of higher SES (37) likely plays a direct role in the accumulation of psychological resilience (38) and cognitive reserve (39). Together, these factors have been shown to have a protective effect on cognition in mid- and late-life and reduce the likelihood of developing dementia (4, 40). Second, with respect to the mediation of these results by indices of deprivation and built environment, we posit that lower levels of deprivation provide individuals with an assortment of benefits which support cognition in later life, and factors specific to rural and coastal regions of the United Kingdom outweigh the oft-reported benefits of coastal/rural living. Regarding the former, we should acknowledge that these results were obtained in a context of abnormally high educational attainment within our sample. It may be that deprivation exerts its influence on cognition via factors such as reduced access to nutritional and/or health-related resources, and higher levels of chronic stress (41, 42). Indeed, chronic stress related to higher levels of deprivation is likely to dysregulate neuro-endocrine activity (i.e., the release of catecholamines and cortisol via hypothalamic–pituitary–adrenal axis) which may negatively affect the efficiency by which neurons are activated during a given task (43) and subsequently alter performance on higher-level cognitive processes (42, 44). In addressing our second point, recall that our results indicate that living in areas with more greenspace and closer to coastlines have a negative effect on cognitive function. This is interesting as the literature mostly contains evidence which supports the positive association between more greenspace and coastal distance and cognition. Besser (45) demonstrates that most papers reviewed describe a positive relationship which is in line with Gascon et al. (27) who found consistent positive associations with blue space and overall health and well-being. An explanation for contrary results presented here may be that living in extensive green or blue (i.e., rural) areas induce feelings of social isolation (46), increasing stress and reducing cognitive performance (see above). These results also emphasize the need to consider the association between cognition and the built environment in a more inclusive socioeconomic/demographic context (e.g., deprivation and education). To that end, we note that the progression of British students into higher education is markedly lower in coastal and rural regions compared to other urban areas (47), and this would likely be associated with higher levels of deprivation in these areas that contributes to subsequent declines in cognition (see above). Asthana and Gibson (47) further explain how social expenditure is lower in deprived coastal areas compared to similarly deprived inland regions, and that investment in education is highly skewed toward the already best performing UK region (i.e., London). Indeed, a report by the UK Department of Education (48) indicates that educational achievement is considerably lower for disadvantaged individuals living in coastal regions compared to their inland counterparts. The needs of these areas to be serviced in terms of educational opportunity may be overlooked because of the incorrect perception of idyllic rural and coastal environments (49), and perhaps due to the positive benefit assumed to be conveyed by coastal and/or rural living [e.g., (24, 50, 51)]. These benefits may be presumed – perhaps incorrectly – to offset the comparative neglect faced by these regions. Our results do provide further evidence supporting a gap in educational attainment between regions of higher and lower deprivation in the United Kingdom, and the regional specificity in which these gaps exist. This disadvantage will likely translate to less access to resources and greater exposure to occupational hazards and psychological stressors (52, 53), lower cognitive reserve (17, 18) and an increased likelihood of developing non-communicable diseases (54) and dementia (23); however, more research is required to better understand why these results occurred.

4.2. Implications

Our results suggest that individuals with higher levels of education are more likely to have easier access to indices of wealth (i.e., a house, a car) and the means by which these indices may be obtained (e.g., a well-paying job). A subsequent implication may be that individuals within a society, and the society as a whole, would be better served to broaden access to means of education, as well as provide more opportunities to become employed. At face value, it may seem that simply providing access to educational resources would be a sufficient solution to provide passive protection to individuals' cognitive health in later life. Of course, access to resources cannot guarantee that individuals make use of them. What is more, what one individual considers to be a stimulating work environment may differ from another, and that our results demonstrate mediation of this relationship by indices of deprivation and built environment indicates the need for region-specific policies rather than blanket solutions. Providing access to traditional education paths should not be the *only* area of focus for policy-makers. Regarding the negative associations between greenspace, coastal distance and cognition, we must first be clear that we do not advocate for the removal of green areas or forcing development away from coastal regions; research included herein describe the cognitive and mental health benefits of greenspace and coastal zones. Instead, they imply that individuals with a higher level of education are more likely to reside and work in urban areas which may be devoid of these features. As briefly discussed in preceding, and rather than directly alter the environment in which people live, policies should be enacted which indirectly mitigate the negative results shown here. For example, chronic stress may be reduced via greater subsidization of individuals and families in disadvantaged situations. Similarly, increased investment in deprived areas in terms of mental health support or general resources may help to curb feelings of stress and support cognitive health. More research is necessary to better understand these relationships before substantive changes to policy can be suggested.

4.3. Limitations and future directions

The above has demonstrated direct and indirect links by which educational attainment supports cognitive function in mid- to late-life. However, we recognize that our work is limited in several methodological aspects which we will outline below. First, years of education does not necessarily predict the *quality* of education received. Of course, many years of poor education would not necessarily impart the same putative benefits as high quality education. Future work should endeavor to model years and quality of education as well as rates of participant literacy to quantify the degree to which either variable predicts cognitive performance. Second, the data used to quantify built environment were not extensive and only examined two commonly assessed variables in this field. Indeed, our model omitted other indicators of built environment such as noise pollution, neighborhood walkability, and environment density. Future work with this cohort should make use of the UKBUMP dataset – a platform with state-of-the-art spatial network analyses to quantify built environments across the United Kingdom (55). We chose to conduct our analyses without this platform in an effort to generalize this model to other cohorts that are without similarly sophisticated built environment composites. Third, our model did not include an index of personal income. This may be perceived as a salient limitation due to the fact it is an oft-used proxy of SES. In addressing this, we note that previous works have outlined how self-reported income, like that in the UK Biobank, may mis-represent individual's real economic status (56), and is a variable which suffers from under-report (30, 57). We note also, that educational attainment, such as what we have included here, has been previously used as a proxy for one's income (58). Fourth, this paper has focused primarily on the level of cognitive performance of individuals at a single point in time. Therefore, no implications can be directly drawn from this work regarding how education may directly or indirectly (i.e., via deprivation and/or built environment) influence the rate of cognitive decline. Further longitudinal research is required to elucidate this relationship. Our study is taken advantage of by the use of data from the UK Biobank; a large cohort composed of over 500,000 individuals which contains one of the most detailed datasets in the world. Unfortunately, this sample is skewed in that it is comprised of a single, highly educated, ethnically homogenous British group with distinct cultural, geographic and economic factors which will likely not be generalizable to other global cohorts. As well, whether this model is generalizable even within different counties of the United Kingdom is a question worth exploring, as strong region-specific differences may drive the nationally represented results which we report here.

5. Conclusion

Our work demonstrates how educational attainment directly and indirectly mediated cognitive function via individual-specific indices of deprivation and built environment. Accordingly, we provide evidence for the need to improve access to education in deprived/underserviced areas in the United Kingdom, as well as the utility in minimizing the gap in objective material deprivation.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://portal.dementiasplatform.uk/.

Ethics statement

The studies involving humans were approved by the UK Biobank Research Ethics Committee (approval letter dated 17, June 2011: Ref 11/NW/0382) and was conducted in accordance with the Declaration of Helsinki. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

BT, MK, CP, VR, and SB designed the study, read, critically revised, and approved the final manuscript. VR and SB provided access to the data. BT, MK, and SB performed the data analysis and interpretation. BT drafted the manuscript with a substantial contribution from all co-authors. VR and SB supervised all stages of this study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1244306/full#supplementary-material

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Associations of handgrip weakness and asymmetry with new-onset stroke in Chinese middle-aged and older adults: a cohort study

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Background: Weak handgrip strength (HGS) has been linked to adverse health outcomes including stroke. However, the joint associations of HGS weakness and asymmetry between limbs with stroke incidence remain underexplored.

Methods: This cohort study analyzed data of participants aged ≥45 years from three waves (2011, 2013, and 2015) of the China Health and Retirement Longitudinal Study. Weak HGS was defined according to the recommendation of European Working Group on Sarcopenia in Older People. Asymmetric HGS was defined if the HGS ratio of both hands was over 1.1 or below 0.9. New-onset stroke was confirmed through self-report of physician's diagnosis.

Results: A total of 10,966 participants without stroke at baseline were included in the analysis. During the 4 years follow-up, there were 262 (2.39%) new-onset stroke cases. Compared to individuals with non-weak and symmetric HGS, those with HGS asymmetry alone and weakness alone were associated with hazards of 1.09 (95% confidence interval [CI]: 0.80–1.48) and 1.27 (95%CI: 0.86–1.88) for new-onset stroke, respectively, while co-occurrence of both HGS asymmetry and weakness was associated with 1.80 (95%CI: 1.24–2.60) greater hazard for new-onset stroke after controlling for confounders. Such associations were consistent in older adults aged ≥60 years, but not in those aged<60 years.

Conclusion: Individuals with both weak and asymmetric HGS tended to have greater risk of new-onset stroke, compared to those with normal HGS, or with either weak or asymmetric HGS alone. Our finding suggested that examining HGS asymmetry alongside weakness may help to improve the risk-stratification and target prevention of stroke, particularly in the older population.

KEYWORDS

handgrip strength, weakness, asymmetry, stroke, cohort study

Background

Globally, stroke is the third leading cause of mortality and a major contributor to long-term disability (1). In 2019, it was responsible for 11.6% of global deaths and 5.7% of the total disability-adjusted life-years (DALYs) (1). With the rapidly ageing population and increases in the prevalence of hypertension and diabetes mellitus in China, the burden of stroke is on the rise, posing an enormous challenge to families and the society as a whole (2, 3). Therefore, identifying modifiable risk factors associated with stroke incidence is of great importance in formulating prevention and treatment strategies.

Handgrip strength (HGS) is a convenient, reliable, and inexpensive assessment of upper limb muscle strength, which could reflect the overall muscle capacity and physical fitness (4). Low HGS has been linked to several adverse health outcomes, including cardiovascular disease, cognitive impairment, disability, and mortality (5–7). Based on the evidence, routine implementation of HGS measurement has been recommended in health care and community settings, especially for the ageing population (6). Nevertheless, most of the current research focuses solely on HGS weakness, while its asymmetry was less discussed (8).

Asymmetric HGS has been found to be detrimental to physical health (9–14). For example, a longitudinal analysis using data from the Health and Retirement Study (HRS) has reported that both HGS weakness and asymmetry independently predicted future activity limitations in Americans aged ≥50 years (9). Likewise, HGS asymmetry has also been found to be a significant predictor of neurodegenerative disorders among Chinese adults aged 60 years and over (10). In addition, several studies have demonstrated a combined effect of HGS weakness and asymmetry on health outcomes, showing greater risks of morbidity accumulation (11), reduced cognitive functioning (12), and functional disability (13, 14) in individuals with both weak and asymmetric HGS.

As the largest organ in the body, skeletal muscle is central to whole-body energy metabolism. Declines in skeletal muscle, reflected by HGS weakness, may result in metabolic dysfunctions like impaired glucose uptake and insulin resistance (15). In addition, HGS weakness has been identified as a risk factor to cardiovascular risk factors, including increased levels of blood pressure (BP), cholesterol, and inflammation (16–18). These conditions can subsequently contribute to an elevated risk of stroke (19–21). Therefore, prospective studies have revealed that HGS weakness was significantly associated with increased risk of stroke (5, 22). However, while HGS asymmetry indicates dysfunction of overall strength capacity, its combined impacts with HGS weakness in the development of new-onset stroke is underexplored. In this study, we aimed to investigate the associations of HGS weakness and asymmetry with the risk of incident stroke among Chinese middle-aged and older adults. Our study may contribute to the establishment of a clinical approach that combines HGS weakness and asymmetry for stroke risk stratification and targeted prevention.

Methods

Study design and population

Data of Chinese adults aged 45 years and older were drawn from the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative survey aiming at promoting scientific research on healthy ageing (23–26). The baseline survey was conducted from June 2011 to March 2012, with participants selected from 450 villages/resident communities across China using a multistage probability-proportional-to-size sampling method. The respondents were followed up every 2 years, with a small share of new participants recruited in each follow-up survey.

In this cohort study, we used data from baseline, 2013, and 2015 follow-up surveys. At baseline, a total of 17,708 participants were recruited (Figure 1). We excluded participants aged under 45 years or without age information ($N = 488$), participants lacking HGS data from both hands ($N = 3,984$) or having HGS measurement only from one hand ($N = 387$), participants with missing information on stroke status ($N = 41$), or body mass index (BMI) ($N = 196$), and participants with prevalent stroke at the baseline survey ($N = 235$), leaving 12,377 eligible participants free of stroke at baseline. We further excluded 741 participants who were lost to follow-up, and 670 participants who lacked information on stroke status in both 2013 and 2015 CHARLS follow-up assessments. Finally, a total of 10,966 participants were included in the current analysis.

The ethics of CHARLS study was approved by the Biomedical Ethics Review Committee of Peking University (IRB approval number: IRB00001052-11015 and IRB00001052-11014) (24). Each participant has signed a written consent form to join the study.

Measurement of handgrip strength

HGS in kilograms was assessed by a standardized dynamometer (Yuejian WL-1000, China) (24, 27, 28). If participants had undergone surgery, or experienced swelling, inflammation, severe pain, or injury to one or both hands within the last 6 months, or declined to have their HGS measured, no assessment was taken. During the assessment, each participant was guided by trained interviewers to stand with their shoulder in a neutral position; if participants were unable to stand without assistance, a sitting position was allowed. They were then instructed to hold the dynamometer with their elbow flexed at a 90° angle and squeeze the handle with their maximum effort for a few seconds. The measurement was repeated twice for each hand.

To define weak HGS, the maximum value of HGS from both hands was used. According to the recommendation of European Working Group on Sarcopenia in Older People (EWGSOP), participants were first stratified into quartiles based on BMI in males and females, respectively. Then, participants with the lowest 20% of HGS in each stratum were defined as having weak HGS. In the current analysis, the cut-off values for weak HGS in females were 19.0, 21.0, 22.0, and 22.5 kg for those with a BMI ≤21.2, 21.3–23.6, 23.7–26.3, and > 26.3 kg/m^2, respectively. The cut-off values for weak HGS in males were 29.0, 32.0, 34.0, and 35.0 kg for those with a BMI ≤20.4, 20.5–22.4, 22.5–25.0, and > 25.0 kg/m^2, respectively.

According to the "10% rule," HGS of the dominant hand is approximately 10% higher than that of the non-dominant hand (13). Therefore, if the HGS ratio of both hands was over 1.1 or below 0.9, the participant was defined as having asymmetric HGS; otherwise, HGS was defined as symmetric.

All participants were further categorized into four groups according to HGS weakness and asymmetry, i.e., no weakness and

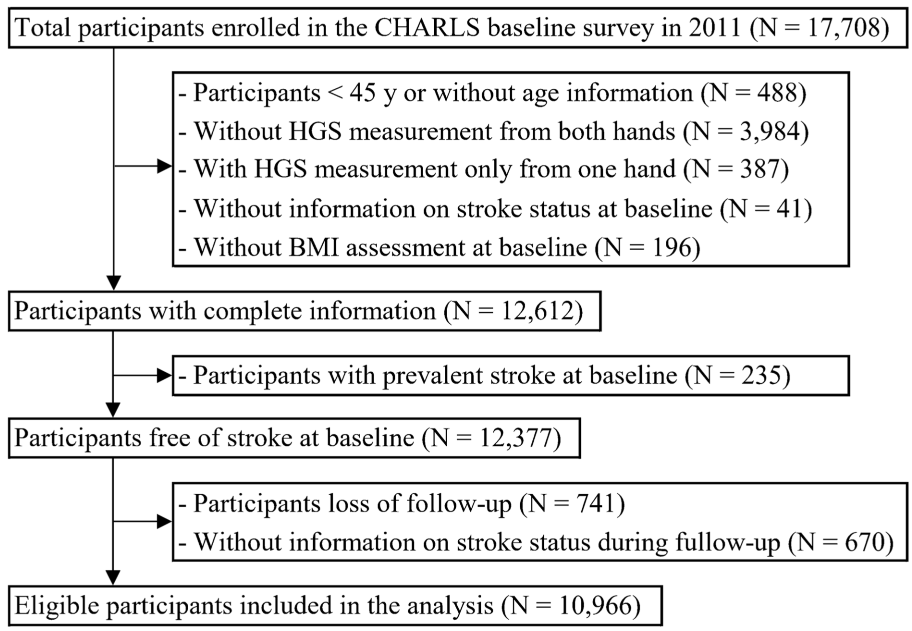

FIGURE 1
Flowchart of participant selection. BMI, body mass index; HGS, handgrip strength.

asymmetry, asymmetry alone, weakness alone, and both weakness and asymmetry.

Measurement of stroke

Self-reported stroke status was assessed by the question "Have you been diagnosed with stroke by a doctor?" (29). Answers to this question were "yes" or "no." A participant was considered as having new-onset stroke if he/she has reported a negative answer at baseline and a positive answer at any of the 2013 and 2015 follow-up surveys. The onset time for stroke was identified as the age at which the stroke was first diagnosed. In cases where this information was absent, we used the midpoint between the most recent wave indicating a stroke diagnosis and the preceding wave when the participant was free of stroke to determine the stroke onset time.

Covariates

Information on age, sex, educational background, marital status, area of residence, smoking and drinking status were collected by trained investigators through face-to-face interviews. Educational background was categorized into three groups: (1) illiterate or without formal education, (2) primary school, and (3) middle school or above. Marital status was classified as married/cohabitated and unmarried groups. Area of residence was divided into rural and urban areas. Ethnicity was classified into Han ethnicity and other ethnic minorities, as the Han ethnicity is the most populous ethnic group in China. Smoking and drinking status were categorized as current users versus non-current users.

BMI was calculated as weight (kg) divided by the square of height (m^2). In the Chinese population, a BMI of 28 kg/m^2 or above was defined as obesity according to the recommendations of Working Group on Obesity in China (30, 31). BP was measured by a digital sphygmomanometer (Omron™ HEM-7200 Monitor, Dalian, China) (24). Glycosylated hemoglobin (HbA1c) and plasma glucose levels were assessed using the affinity high-performance liquid chromatography (HPLC) and the enzymatic colorimetric test, respectively. Physician-diagnosed diabetes mellitus, hypertension, dyslipidemia, and heart diseases were self-reported by each participant. Hypertension was ascertained if one or more of the following criteria was met: (1) with physician-diagnosed hypertension, (2) a mean systolic BP $\geq$ 140 mmHg, (3) a mean diastolic BP $\geq$ 90 mmHg, and (4) on anti-hypertensive drugs (32, 33). According to the American Diabetes Association criteria, a participant was defined as having diabetes mellitus if he/she had random plasma glucose $\geq$11.1 mmol/L, and/or fasting plasma glucose $\geq$7.0 mmol/L, and/or HbA1c $\geq$ 6.5%, and/or with self-reported physician-diagnosed diabetes mellitus, and/or on glucose-lowering drugs or insulin treatment (34–36).

Statistical analysis

Descriptive statistics were expressed as mean ± standard deviation (SD) for continuous data and number (percentage) for categorical data. Characteristics across different HGS weakness and asymmetry groups were compared using one-way analysis of variance (ANOVA) test for continuous data and χ^2 test for categorical variables. Cox proportional hazards regression analyses were used to examine the association between different HGS weakness and asymmetry status and the risk of new-onset stroke. Participants with no weakness and asymmetry was treated as the reference group in all models. The association was first assessed in a crude model. The adjusted model was controlled for age, sex, educational background, marital status, area of residence, current smoking and drinking status, BMI (not adjusted in weak HGS-related analysis), diabetes mellitus, hypertension, dyslipidemia, and heart diseases, according to previous similar studies (5, 22, 37). The results were presented as hazard ratio (HR) with 95% confidence interval (CI).

Three sensitivity analyses were further conducted to test the robustness of the findings: (1) we examined the associations in different age groups, i.e., <60 years and ≥ 60 years, (2) we excluded participants who developed stroke within the first 2 years of follow-up to avoid reverse causality, and (3) we defined asymmetric HGS if the HGS ratio of both hands was over 1.2 or below 0.8 to test the robustness of the findings.

Data analyses were performed with Stata/SE 15.1 (Stata-Corp, College Station, TX, United States). All tests were two-sided and a value of p <0.05 was considered to be statistically significant.

Results

Of the 10,966 participants aged 45 years or older, 5,781 (52.7%) were females and the mean age was 59.2 ± 9.4 years at baseline. Figure 2 depicts a histogram of the HGS ratio among participants, showing that the majority (58.7%) had symmetric HGS, i.e., HGS ratio between 0.9 and 1.1. The number of participants with non-weak and symmetric HGS, asymmetric HGS alone, weak HGS alone, and both weak and asymmetric HGS were 5,232 (47.7%), 3,443 (31.4%), 1,205 (11.0%), and 1,086 (9.9%), respectively (Table 1). Compared to participants without HGS weakness or asymmetry, those with both weak and asymmetric HGS were older, more likely to be females, unmarried, less educated, less obese; and they were also more likely to have higher levels of systolic BP and glucose profiles, and with higher prevalence of self-reported chronic diseases, including diabetes mellitus, hypertension, dyslipidemia, and heart diseases.

During 4 years of follow-up, there were 262 (2.39%) new-onset stroke cases. Compared to non-weak HGS group, those with HGS weakness were more likely to develop stroke (2.01% versus 3.84%, $p < 0.001$) (Table 2). In contrast, the incidence of stroke was comparable between participants with or without asymmetric HGS (2.72% versus 2.16%, $p = 0.060$). When weakness and asymmetry of HGS were taken into consideration at the same time, we found that participants with both conditions had the highest incidence rate of stroke compared to the other three groups ($p < 0.001$).

The association of baseline HGS weakness and asymmetry with the risk of new-onset stroke was presented in Table 2. In the crude model, weakness was associated with 1.95 times (95%CI: 1.51–2.51) greater risk of future stroke attack, whereas asymmetry was not significantly associated with the risk of stroke (HR: 1.26, 95%CI: 0.99–1.61). The findings were consistent in fully adjusted models. When HGS weakness and asymmetry were considered at the same time, using non-weak and symmetric HGS as reference, individuals with both weak and asymmetric HGS tended to have elevated risk of stroke (adjusted HR: 1.80, 95%CI: 1.24–2.60) compared to those with weakness alone (adjusted HR: 1.09, 95%CI: 0.80–1.48) or asymmetry alone (adjusted HR: 1.27, 95%CI: 0.86–1.88), albeit the confidence intervals were generally overlapped. Subgroup analysis by age showed similar associations in participants aged ≥60 years, but not in their counterparts who were younger than 60 years (Supplementary Table S1). Consistent results were also found after excluding incident stroke in 2013 CHARLS survey (Supplementary Table S2) or using a different criterion for asymmetric HGS (Supplementary Figure S1).

Discussion

The present study reported the individual and joint associations of HGS weakness and asymmetry with new-onset stroke among middle-aged and older Chinese in a cohort setting. We demonstrated that individuals with both weak and asymmetric HGS had a tendency of increased risk of new-onset

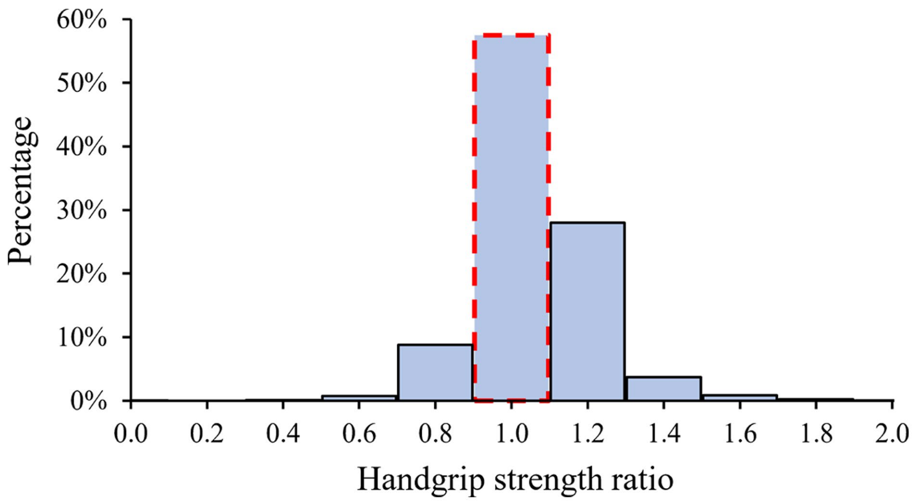

FIGURE 2
Histogram of HGS ratio. Participants with a HGS ratio over 1.1 or below 0.9 were defined as having asymmetric HGS; otherwise, symmetric HGS was defined. HGS, handgrip strength.

TABLE 1 Comparison of baseline characteristics by HGS weakness and asymmetry.

	No weakness and asymmetry	Asymmetry alone	Weakness alone	Both weakness and asymmetry	*p* value
N (%)	5,232 (47.7%)	3,443 (31.4%)	1,205 (11.0%)	1,086 (9.9%)	
Demographic and lifestyle factors					
Mean age (years)	57.4 (8.4)	58.0 (8.7)	65.0 (9.5)	65.6 (10.3)	<0.001
Female, *n* (%)	2,646 (50.6%)	1922 (55.8%)	592 (49.1%)	621 (57.2%)	<0.001
Educational background, *n* (%)					<0.001
Illiterate/no formal education	2,226 (42.6%)	1,529 (44.4%)	712 (59.1%)	660 (60.9%)	
Primary school	1,193 (22.8%)	781 (22.7%)	263 (21.8%)	225 (20.8%)	
Middle school or above	1,812 (34.6%)	1,133 (32.9%)	230 (19.1%)	199 (18.4%)	
Area of residence, *n* (%)					0.328
Urban	3,375 (64.5%)	2,203 (64.0%)	804 (66.7%)	713 (65.7%)	
Rural	1,857 (35.5%)	1,240 (36.0%)	401 (33.3%)	373 (34.3%)	
Marital status, *n* (%)					<0.001
Unmarried/cohabitated	478 (9.1%)	377 (10.9%)	238 (19.8%)	234 (21.5%)	
Married	4,754 (90.9%)	3,066 (89.1%)	967 (80.2%)	852 (78.5%)	
Ethnicity, *n* (%)					0.168
Han ethnicity	4,818 (92.1%)	3,145 (91.4%)	1,111 (92.3%)	1,015(93.5%)	
Ethnic minorities	413 (7.9%)	296 (8.6%)	93 (7.7%)	71 (6.5%)	
Current smoker, *n* (%)	1,713 (32.9%)	1,031 (30.0%)	365 (30.4%)	283 (26.3%)	<0.001
Current drinker, *n* (%)	1,922 (36.8%)	1,101 (32.0%)	356 (29.5%)	259 (23.9%)	<0.001
Clinical / biochemical measures					
BMI (kg/m^2)	23.5 (3.7)	23.5 (3.9)	23.5 (4.2)	23.2 (4.0)	0.040
Obesity, *n* (%)	589 (11.3%)	410 (11.9%)	139 (11.5%)	96 (8.8%)	0.048
Systolic BP (mmHg)	129.5 (20.5)	130.0 (21.0)	134.3 (23.1)	133.8 (23.7)	<0.001
Diastolic BP (mmHg)	76.0 (12.1)	76.2 (12.2)	75.7 (12.7)	75.1 (12.0)	0.053
Glucose (mmol/L)	6.1 (1.9)	6.0 (1.8)	6.4 (2.6)	6.4 (2.6)	<0.001
HbA1c (%)	5.2 (0.8)	5.2 (0.7)	5.4 (1.0)	5.4 (1.0)	<0.001
Total cholesterol (mmol/L)	5.0 (1.0)	5.1 (1.0)	5.0 (1.0)	5.0 (1.1)	0.051
Triglycerides (mmol/L)	1.5 (1.3)	1.5 (1.2)	1.5 (1.3)	1.5 (1.1)	0.456
HDL-cholesterol (mmol/L)	1.3 (0.4)	1.3 (0.4)	1.3 (0.4)	1.3 (0.4)	0.127
LDL-cholesterol (mmol/L)	3.0 (0.9)	3.1 (0.9)	3.0 (0.9)	3.0 (0.9)	0.038
Disease history					
Diabetes mellitus, *n* (%)	607 (11.6%)	386 (11.2%)	199 (16.5%)	169 (15.6%)	<0.001
Hypertension, *n* (%)	1,926 (36.8%)	1,343 (39.0%)	586 (48.6%)	534 (49.2%)	<0.001
Dyslipidaemia, *n* (%)	399 (7.8%)	312 (9.2%)	118 (10.0%)	97 (9.2%)	0.019
Heart diseases, *n* (%)	504 (9.7%)	386 (11.3%)	151 (12.6%)	183 (16.9%)	<0.001

BMI, body mass index; BP, blood pressure; HbA1c, glycated hemoglobin A1c; HDL, high-density lipoprotein; HGS, handgrip strength; LDL, low-density lipoprotein; SD, standard deviation. Continuous data were reported as mean (SD) and categorical data were reported as frequency (percentage).

stroke, compared to those with normal HGS, or with either weak or asymmetric HGS alone. Our findings highlighted the importance of examining HGS asymmetry alongside its weakness to improve the risk-stratification and target prevention of stroke.

The significant association between HGS weakness and incident stroke has been demonstrated by several previous studies (5, 22, 38). For example, the Prospective Urban Rural Epidemiology (PURE) study with data from 17 countries has reported a 9% increased risk of incident stroke associated with every 5 kg reduction in HGS (5). A

TABLE 2 Associations of HGS weakness and asymmetry with the risk of new-onset stroke.

	Stroke incidence	Crude model		Adjusted model[a]	
		HR (95%CI)	*p* value	HR (95%CI)	*p* value
HGS weakness					
No weakness	2.01%	Ref	–	Ref	–
Weak HGS	3.84%	1.95 (1.51, 2.51)	<0.001	1.46 (1.10, 1.93)	0.009
HGS asymmetry[b]					
No asymmetry	2.16%	Ref		Ref	
Asymmetry HGS	2.72%	1.26 (0.99, 1.61)	0.060	1.21 (0.94, 1.55)	0.138
HGS weakness and asymmetry					
No weakness and asymmetry	1.93%	Ref		Ref	
Asymmetry only	2.12%	1.10 (0.81, 1.49)	0.534	1.09 (0.80, 1.48)	0.579
Weakness only	3.15%	1.66 (1.14, 2.41)	0.008	1.27 (0.86, 1.88)	0.236
Both weakness and asymmetry	4.60%	2.43 (1.73, 3.41)	<0.001	1.80 (1.24, 2.60)	0.002

HGS, handgrip strength; HR, hazard ratio; CI, confidence interval.
[a]Adjusted for age, sex, educational background, marital status, area of residence, current smoking and drinking status, diabetes mellitus, hypertension, dyslipidaemia, and heart diseases.
[b]When the exposure was HGS asymmetry, BMI was also adjusted.

cohort study of over 280,000 participants from UK biobank has also revealed that weak HGS was linked to a higher hazard for both ischemic and hemorrhagic stroke (38). Moreover, a prospective cohort study using data from CHARLS has reported that weakness and declines in HGS were associated with stroke incidence in middle-aged and older Chinese (22). In accord with above-mentioned studies, we also demonstrated that HGS weakness was associated with increased risk of stroke.

The exact mechanisms underlying the association between HGS weakness and risk of stroke are not fully understood. Skeletal muscle is a major organ of energy metabolism, and when muscle mass is reduced, the uptake of glucose is decreased accordingly. This reduction can subsequently lead to insulin resistance (15), a well-established risk factor of stroke (19). Furthermore, previous studies have demonstrated that HGS weakness was associated with increased level of inflammatory factors (18), such as C-reactive protein and interleukin-6, which in turn could contribute to a heightened vulnerability to stroke incidence (20). In addition, weak HGS might be a product of long-term unhealthy lifestyles and imbalanced nutrition (39, 40). These factors are associated with an increased risk of stroke, irrespective of age (41, 42). Therefore, the significant association between HGS weakness and new-onset stroke appears to be physiologically plausible.

Compared to HGS weakness, the association between HGS asymmetry and health outcomes has been underexplored. A cohort analysis using data from CHARLS has demonstrated that individuals with asymmetric HGS had increased hazard of neurodegenerative disorders during the 4 years follow-up, whereas HGS weakness was not an independent contributor to the outcome (10). Another longitudinal study with over 18,000 American adults aged 50 years or above has shown that HGS asymmetry and weakness were independently associated with increased risk of morbidity accumulation, while the odds were even greater in individuals with co-occurrence of the two conditions (11). Similar findings regarding the combined effect of HGS asymmetry and weakness have also been reported on incident functional disabilities (13, 14), low cognitive function (12), and depression (43). Our study further extends the knowledge of previous studies by demonstrating an augmented risk of stroke in individuals with both weak and asymmetric HGS, albeit no significant association was observed when examining the individual association of HGS asymmetry with new-onset stroke. The exact mechanism underlying the increased risk estimates of stroke in participants with both weak and asymmetric HGS remains unclear. Strength asymmetry between limbs might be a precursor of declines in overall strength capacity, and the co-occurrence of HGS weakness and asymmetry might represent a more severe muscle dysfunction than either condition alone (11). This may help explain the exaggerated risk of stroke in participants with both weak and asymmetric HGS. As such, our study further supports the combined assessments of HGS weakness and asymmetry in health screening to identify high-risk individuals for target prevention of stroke.

Subgroup analysis by age further showed that the associations remained consistent in adults aged ≥60 years, while such associations became statistically non-significant in individuals below 60 years. The mechanisms driving this variation are yet to be fully elucidated. In our study sample, younger adults aged <60 years generally achieved higher educational levels. This could potentially render them more perceptive and responsive to weak HGS, subsequently reducing their stroke risk. In addition, middle-aged individuals usually maintain a more active lifestyle compared to their older counterparts. This heightened physical engagement might mitigate the associations between HGS and stroke susceptibility in the younger population. Our research underscores the importance of HGS monitoring and intervention, particularly in the older population.

Strengths and limitations

The major strength of our study is the cohort design with a nationwide sample using standardized protocols. We not only investigated the individual impact of HGS asymmetry and weakness on stroke incidence, but also the combined impact. However, there are still some limitations that deserve further discussion. First, stroke was defined based on self-report of a physician's diagnosis, which might cause potential recall bias and misclassification of stroke. Nevertheless, chronic diseases reported by participants has been demonstrated to be reliable compared with information extracted from medical record (44, 45). In addition, in longitudinal studies, the bias from such misclassification is often non-differential with respect to stroke outcome events, thus biasing the measure of association towards the null. Consequently, our results were likely more conservative than the true association. Second, since brain images were not applied to determine history of stroke at baseline, we could not rule out the possibility of minor stroke or transient ischemic attack (TIA) without typical symptoms or medical diagnosis. Nevertheless, it is usually not feasible to do so for every participant in large epidemiological study. The sensitivity analysis excluding incident stroke cases in the first 2 years of follow-up also revealed augmented risk of stroke in participants with both weak and asymmetric HGS, suggesting the robustness of our findings. Third, there was no information regarding the types of stroke attack. Therefore, we were unable to differentiate whether HGS weakness and asymmetry had different associations with ischemic and hemorrhagic stroke. Fourth, although many confounders have been controlled in the statistical models, we could not rule out potential residual confounding effects of other factors that were not captured in the present study, such as family history of stroke or dietary pattern and quality (46–49). In addition, although physical activity is recognized as an important risk factor for stroke (50), it was not included in the analysis due to the lack of data for 58.3% of the included participants. Furthermore, the modified International Physical Activity Questionnaire (IPAQ)-short form used in CHARLS adopted categorical choices to collect participant's time spent on different intensities of physical activity, which might lead to imprecise estimates of energy expenditure and physical activity levels. Therefore, we did not consider this factor in the current study. Future research should further investigate whether physical activity could alter the associations observed in the present study.

Conclusion

Our study demonstrated that HGS weakness in combination with its asymmetry was associated with an increased risk of new-onset stroke in Chinese middle-aged and older adults. The risk estimates tended to be larger than that observed in individuals with normal HGS, or those only with weak HGS or asymmetric HGS. Our findings could provide valuable insights into early identification and intervention for stroke development. Targeting individuals with both weak and asymmetric HGS might have substantial benefits in lowering the risk of stroke. However, future randomized controlled trials are needed to confirm the conclusion.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found in a public, open access repository, and can be accessed at China Health and Retirement Longitudinal Study (CHARLS) http://charls.pku.edu.cn/index/en.html. Requests to access the datasets should be directed to https://charls.pku.edu.cn/en/. The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The ethics of CHARLS was approved by the Biomedical Ethics Review Committee of Peking University (IRB approval number: IRB00001052-11015 and IRB00001052-11014) in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in CHARLS. The current study is a secondary data analysis based on the public data of CHARLS, which is exempt from further ethical approval according to relevant regulations.

Author contributions

BC and VG: conceptualization and supervision. VG: data curation. YZ and VG: formal analysis, funding acquisition, and writing – original draft. YZ, WC, BC, JL, and VG: methodology. WC, BC, LL, and VG: validation. YZ, WC, BC, LL, JL, and VG: writing – review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1251262/full#supplementary-material

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Determinants and indicators of successful aging as a multidimensional outcome: a systematic review of longitudinal studies

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Background: Successful aging (SA) has been coined as a term to describe the multidimensional aspects associated with achieving optimal combination of physical and mental health along with social well-being health, mental and social well-being at older age. In recent years there has been an increased interest in understanding the role of determinants of SA, such as demographic, biological, behavioral, psychological and social factors. To synthesize the recent evidence, we conducted a systematic review of longitudinal studies on a range of determinants and indicators of SA defined as a multidimensional outcome.

Methods: A systematic search of PubMed, MEDLINE and Web of Science for finding eligible papers published between August 2016 and June 2023 was conducted following the Preferred Reporting Items for a Systematic Review and Meta-Analysis (PRISMA) guidelines. The review protocol was registered in PROSPERO International Prospective Register of Systematic Reviews (Registration number: CRD42021250200). The web-based automated screening tool–Rayyan–was used for title and abstract screening. The study quality was assessed using the Quality in Prognosis Studies (QUIPS) tool.

Results: A total of 3,191 records were initially identified using the predefined search strategy. Out of 289 articles selected for full text screening, 22 were found eligible and included in the review. A variety of factors have been explored in relation to SA, ranging from socio-demographic factors, nutrition, lifestyle, biological pathways, psychological health, and well-being. Overall, the results of recent studies have confirmed the role of metabolic health, adherence to healthy dietary patterns, such as the Mediterranean diet, physical activity, non-smoking, and higher socio-economic status as main factors associated with higher odds for SA. Emerging research highlights the role of psycho-social factors and early life health as determinants of SA.

Conclusion: In summary, this review highlights the importance of healthy living and monitoring metabolic risk along with sustaining psychological well-being in adult life as major determinants of SA. Further methodological and research work on SA would pave the way toward development of adequate health promotion policies in aging societies.

Systematic review registration: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42021250200, CRD42021250200.

KEYWORDS

successful aging, determinants, lifestyle factors, metabolic health, well-being, systematic review

1 Introduction

The world's population is aging at an unprecedented pace. By 2050, it is estimated that the global number of people aged 65 and older will be more than double, reaching over 1.5 billion individuals (1). The marked increase in the proportion of older people has posed new challenges to public health systems and societies across the globe (2). How to cope with the increasing burden of age-related diseases and conditions has become a point of major concern to health policy makers (3). To address this question, it is not only vital to understand drivers of chronic disease development, but also determinants that ensure overall health and well-being at older age. The concept of successful aging (SA) was introduced by Rowe and Kahn in 1997 to describe the phenomenon of aging in good overall physical, mental, and social wellbeing (4). Originally defined as 'freedom from disease or disease-disability, high cognitive and physical functioning, and active engagement with life', the term SA has evolved to include functional ability, independence and quality of life that assure not only living longer but also preserving health and wellbeing until old age (5–7). There has been increasing interest in understanding the role of various exposures throughout the life-course including lifestyle, biological, psychological, and social factors as possible determinants of SA. Several reviews have been previously conducted to evaluate determinants of SA. However, those reviews were focused on specific factors, such as physical activity (8, 9), smoking and alcohol consumption (10), diet (11, 12), and psychosocial factors (13, 14). So far, only one review provided a comprehensive overview of a wider range of determinants including demographic, biological, behavioral, psychological and social factors summarizing evidence published by August 2016 (15). With the continuously increasing interest in the topic, numerous new studies have been published in the recent years. However, the newly emerging evidence has not been summarized yet.

We therefore conducted a systematic review to synthesize the recent evidence from published longitudinal studies on a range of determinants and indicators of SA to identify existing gaps and guide planning of future studies and the development of tailored interventions and policies addressing healthy longevity.

Abbreviations: ALA, Amino leavulinic acid; BMI, Body Mass Index; CRP, C-reactive Protein; DHA, Docosahexaenoic acid; DPA, Docosapentaenoic acid; EPA, Eicosapentaenoic acid; N3-PUFA, Omega 3 polyunsaturated fatty acids; PRISMA, Preferred Reporting Items for a Systematic Review and Meta-Analysis; QUIPS, Quality in Prognosis Studies; RoB, Risk of Bias; SA, Successful Aging.

2 Methods

2.1 Search strategy and selection criteria

The review protocol has been developed and registered in PROSPERO International Prospective Register of Systematic Reviews (Registration number: CRD42021250200). The review was written following the Preferred Reporting Items for a Systematic Review and Meta-Analysis (PRISMA) guidelines (16). To enable full exploration of the literature on the topic, no setting restrictions were applied. A systematic search was performed identifying records in PubMed, MEDLINE, and Web of Science published between August 2016 and June 2023 in order to depict literature published after a previous review on the topic (15). The following terms were included in our search methodology: (1) outcome defining terms: "healthy aging" OR "healthy aging" OR "successful aging" OR "successful aging" OR "positive aging" OR "positive aging" OR "productive aging" OR "productive aging" OR "aging well" OR "aging well" OR "effective aging," and (2) exposure defining terms: "smoking" OR "tobacco" OR "cigarette*" OR "physical activity" OR "physical inactivity" OR "exercise*" OR "alcohol" OR "alcohol drinking" OR "diet" OR "nutrition" OR "quality of life" OR "health" OR "physical health" OR "physiological well-being" OR "metabolic health" OR "mental health" OR "cognitive function" OR "social well-being" OR "factor*" OR "indicator*" OR "correlate*, and (3) "study type defining terms: "longitudinal" OR "cohort stud*."

A summary of the inclusion and exclusion criteria and rationale is presented in Supplementary Table S1. Only longitudinal observational studies, where exposures were measured before the outcome, were included in the review. Further inclusion criteria included: (a) original research articles published in peer-reviewed journals; (b) primary aim to measure associations between determinants and SA outcome; (c) using the definition of SA based on the multidimensional model of SA by Rowe and Kahn, i.e., including at least some aspects within the predefined criteria: (1) absence of chronic disease and disability; (2) good physical and cognitive functioning and (3) engagement with life (sustained engagement in social and productive activities); (d) community-dwelling populations; (e) baseline age of participants being >18 years. Exclusion criteria were: (a) cross-sectional and case–control studies, experimental laboratory or animal studies, and methodological studies; (b) secondary source reports (including literature reviews, books, consensus statement, expert meetings, policy recommendations, and author opinions); (c) SA definitions not including the aforementioned domains of SA as defined by Rowe and Kahn; (d) studies in special population groups, i.e., pregnant women, diseased individuals, institutionalized individuals, and centenarians. Determinants and indicators of SA explored in this review were organized into the following four domains: (1) socio-demographic; (2) nutrition and lifestyle-related; (3) biological; and (4) psychological factors and well-being.

2.2 Study selection

Identified records were imported into the Rayyan, a web-based automated screening tool for systematic reviews (17). Titles and abstracts were then screened by two independent reviewers (RAA, AWES). Any conflict between the two reviewers was resolved by a third independent reviewer (CER). Full-text articles were retrieved if the article was considered eligible and subjected to a second evaluation by three independent reviewers (RAA, AWES, and CLG). Any discrepancies and disagreements in the full-text screening were discussed and resolved by consensus among three independent reviewers (CER, KA, and MB). After retrieval of full-text articles, the reference lists of selected articles were additionally cross-checked to identify further articles of relevance.

2.3 Data extraction

The data extraction was performed by two reviewers (AWES and CER) using a predefined data extraction form. The following information was extracted: first author, publication year and country, study design, study population, sample size, details on composition and measurement of SA outcome, details on assessed determinants, and reported effect estimates for associations with the SA outcome. When a study provided several effect-estimates with adjustment for different sets of covariates, results were reported based on the one adjusting for the largest number of covariates.

2.4 Assessment of risk of bias

The quality assessment of the included studies was performed by three independent reviewers (RAA, AWES, and CER) using the Quality in Prognosis Studies (QUIPS) tool. The QUIPS tool was developed to assess the risk of bias (RoB) in studies on prognostic factors (18). The specific questions and assigned points of the QUIPS tool are presented in Supplementary Tables S2–S8, respectively. The overall RoB for each study was evaluated based on the bias domains including study participation, study attrition, outcome measurement, study confounding, as well as statistical analysis and reporting. Each study was assigned an overall bias rating of low, medium, or high, based on the assessment of each separate bias domain.

3 Results

3.1 Study selection

A total of 3,191 records were initially identified in PubMed, MEDLINE, and Web of Science using the defined search strategy (Figure 1). After excluding duplicates ($n = 6$), the title and abstract of a total of 3,185 records were screened. Of these, 2,896 were deemed ineligible and 289 records remained for full-text screening. Of these, 273 articles were excluded due to inappropriate outcome ($n = 120$), inappropriate study design ($n = 87$), outcome not a composite measure of SA ($n = 48$), inappropriate publication format ($n = 12$), full-text article not found ($n = 3$), publication was part of a previous review ($n = 2$), full-text not in English ($n = 1$). Following the full-text screening, 16 articles were found eligible according to the proposed inclusion and exclusion criteria and their reference lists were screened for the identification of potential eligible studies, retrieving a total of 6 additional articles. In total, 22 articles met the selection criteria and were therefore included in the systematic review (19–40). Figure 1 shows the PRISMA flowchart with studies included and excluded at each step of the systematic review process.

3.2 Study characteristics

The study characteristics of the included reports are presented in Table 1. The respective sample sizes ranged from 210 (35) to 52,135 (37) participants. Regarding the geographical setting, 10 of the studies were conducted in European countries, namely France (24, 30–32, 38), United Kingdom (28), Finland (19, 29), Spain (33), and the Netherlands (36). Six studies were conducted in the United States (22, 25–27, 34, 37), two studies in Australia (39, 40), one study in Brazil (35), and three studies in Asia, with one study in Taiwan (23), one in Indonesia (21), and one in China (20). Figure 2 provides a graphical representation of the distribution of the geographical areas covered by the studies included in the review. Most studies recruited both male and female participants, with only two studies including exclusively females (26, 37), and one study male participants only (29). The follow-up time ranged from five (24) to 36 (29) years. All but three studies included participants aged 45 years or older at study baseline (22, 29, 31, 37).

3.3 Determinants of successful aging

An overview summarizing the results for the reported associations of socio-demographic, nutritional, lifestyle, psychological, and biological factors with SA is presented in Table 2. Figure 3 additionally provides a summary of the main determinants shown to be statistically significantly associated with SA based on the studies included in the systematic review. More details of these associations are provided below.

3.3.1 Socio-demographic factors

Among the demographic factors, sex was the most reported determinant of SA ($n_{studies} = 5$, $n_{participants} = 19{,}020$). Female sex was associated with lower odds for SA in three studies ($n = 13{,}607$) (21, 25, 36). Vice versa, it was associated with higher odds for SA in another study ($n = 3{,}527$) (35). One study found no association between sex and SA ($n = 1{,}886$) (33). Being of black or Hispanic ethnicity, as well as being in debt were negatively associated with SA in the Health and Retirement Study from the United States ($n = 12{,}108$) (25). Furthermore, in the same population, a higher household income was positively associated with SA, but not childhood financial adversity (25). In the Spanish population of the COURAGE Europe Project, a higher occupational status was positively associated with SA, whereas no association was present in individuals that never were employed (33).

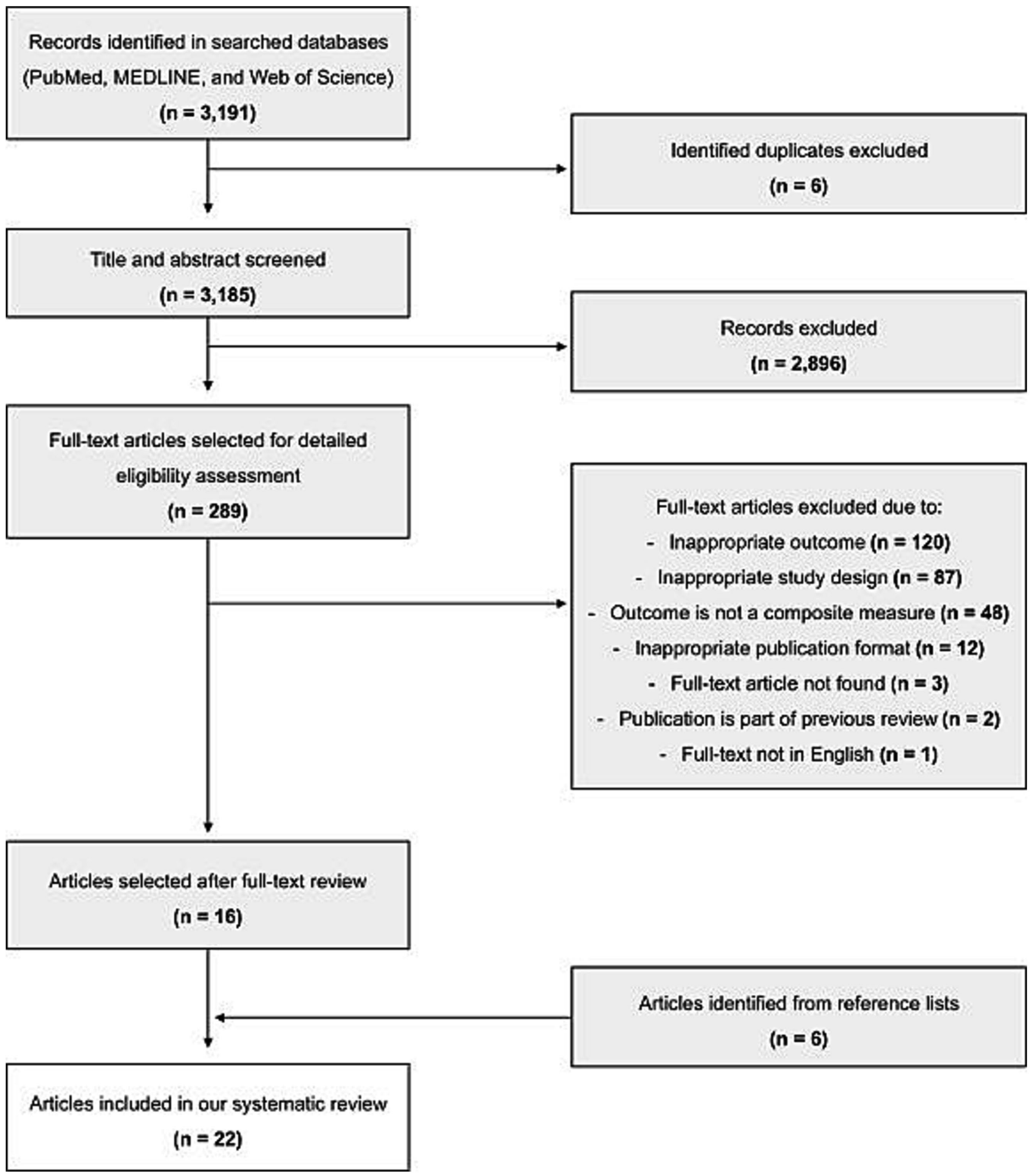

FIGURE 1
PRISMA flow diagram of study selection, including identification, screening, eligibility, and inclusion of studies.

Results about the association between residency and SA have been reported in two studies. Cooney et al. (25) did not find an association between SA and residency in the south compared to other regions in the United States. The South region was described "to have the lowest median household income, and highest poverty rate and rate of uninsured individuals in the population." In a Spanish study, rural residence as compared to urban residence was associated with higher odds for SA (33). This entails several dimensions such as demographics, access to health services, intergenerational and other social relationships (41). Furthermore, no association with SA was found for marital status (33) and age of the oldest living parent indicating family longevity (25).

3.3.2 Nutrition and lifestyle factors

Anthropometrics and lifestyle factors were the most explored factors in the domain *nutrition and lifestyle*. Four studies reported results on the role of anthropometric indicators of nutritional status as determinants of SA suggesting that taller height as an accumulation of "genetic endowment and various early-life exposures" (37) and higher body mass index (25, 29, 38) were negatively associated with SA. Interestingly, Ma et al. (37) reported that the lower odds for SA in taller individuals could be modulated by a diet rich in fruits and vegetables. Four studies reported positive associations between adherence to dietary recommendations, including the French dietary guidelines (24, 30), the Australian dietary recommendations (40), and the Mediterranean diet (31) with SA. Concerning beverages, low alcohol consumption was associated with SA when examined in context of an overall healthy diet (31, 32) but not when the univariate association was examined (31). However, moderate alcohol consumption was associated with SA in another study by Urtamo et al. (29). The same study also reported null findings on coffee consumption. Gopinath et al. (40) reported null findings on the consumption of non-alcoholic beverages and the association with SA. In addition to dietary patterns, several studies further explored the association between specific nutrients and SA. Gopinath et al. (39) reported that high fiber intake was positively, while a high glycaemic index was negatively associated with SA. Lai et al. (34) found that higher levels of circulating omega 3 fatty acids were positively associated with SA. More specifically, high eicosa- and docosapentaenoic acid were positively associated, whereas alpha linolic and docosahexaenoic acid levels were not associated with SA, respectively (34).

Beyond individual behaviors, several studies explored combination of lifestyle factors in relation to SA. Based on data from the French" Supplémentation en Vitamines et Minéraux Antioxydants" (SU.VI.MAX) cohort, Atallah et al. (32) assessed the combined impact of lifestyle factors (weight, smoking status, physical activity, alcohol consumption, and diet) modeled as a healthy lifestyle index on SA. Each point increase in the lifestyle index was associated with an 11% higher probability of SA. The proportions of SA attributable to specific factors were 7.6, 6.0, 7.8, and 16.5% for body mass index, physical activity, diet quality, and smoking status, respectively. Lee-Bravatti et al. (22) explored a combination of lifestyle factors that included physical activity, smoking, sleep, and diet among older Puerto Rican adults. The authors found that the constructed lifestyle score was more strongly associated with SA than individual behaviors alone, suggesting that there are synergistic effects at play. Furthermore, the study highlighted physical activity, never smoking, and higher quality of sleep to play a dominant role in affecting SA. Overall, these studies underline the importance of healthy lifestyle habits at midlife as determinants of overall health during aging.

3.3.3 Biological factors

In recent years, the number of studies that explored biological pathways as intermediary determinants of SA has increased. Ruhunuhewa et al. (38) reported that impaired metabolic health, defined by high triglyceride levels or lipid-lowering drug use, high blood pressure, high blood glucose levels, high total cholesterol, and low high-density lipoprotein cholesterol, was negatively associated with SA. Furthermore, Lassale et al. (28) found that in individuals aged between 47 and 87 years at baseline, increasing CRP levels over the course of 10 years of follow-up presented lower odds for SA than those that had stable low CRP trajectories. In a more recent study, Lin et al. (23) explored the association of the metabolic syndrome and its components (central obesity, elevated blood glucose, low high-density lipoprotein cholesterol, and hypertension) with SA. The results supported the previously reported link between metabolic health and SA, showing that it may be important not only for physical health, but also may determine psychological well-being.

3.3.4 Psychological factors and well-being

The association of psychological factors and well-being with SA has been explored by four studies. In the Health and Retirement Study, higher optimism was associated with SA for both males (27) and females (26, 27), although the association was found to be stronger in males. Self-perceived health was considered as an indicator for SA in two studies. Urtamo et al. (29) assessed self-rated health and found a positive association with SA. Cooney and Curl (25) investigated self-reported childhood health and reported poor health to be negatively associated with SA. Furthermore, based on data from the Helsinki Aging Study, Aalto et al. observed that participants who characterized themselves as "feeling needed" and "having plans for the future" had higher odds for SA (19). Most studies assessed SA as a binary outcome, except from six studies that used a continuous outcome, i.e., by means of a numerical score (22, 27, 28, 32, 33, 36). Following the conceptual definition of Rowe and Kahn's model (4), all selected studies included in our review defined SA as a multidimensional outcome and included different aspects of the major proposed domains. Specific components of SA that depicted the first two domains, namely *absence of chronic disease* as well as *disability and good physical and cognitive functioning* included favorable state of respiratory function (28, 39, 40), blood pressure (23, 28), cardiovascular health (39, 40), absence of pain that limits function (20, 24, 30–32, 36, 38), and self-rated health (19, 24, 30–32, 36, 38). The *engagement with life* domain was largely defined as the lack of limitations on social functioning in six out of nine studies (24, 25, 30–32, 36, 38). One study included *happiness* as an additional component of SA (29). Methods of assessment and measurement scales of the individual components of SA varied extensively throughout the studies with no standardized definition of SA used across the studies.

3.4 Risk of bias assessment

The results of the RoB assessment are presented in Figure 4. Overall, the RoB was *low* in 13 out of 22 included studies, while six and three studies presented *moderate* and *high* RoB, respectively. The high RoB score was explained by ratings on study attrition and lack of confounder control. Moreover, study attrition was rated *medium* RoB in 15 out of 22 studies, and as *high* in the remaining seven studies.

4 Discussion

The current review provides a summary of the recent research on determinants of SA, including socio-demographic factors, nutrition, lifestyle, biological pathways, psychological health, and well-being. Overall, a higher socio-economic status, adherence to healthy plant-based diet such as the Mediterranean diet, not smoking, being physically active, and being metabolically healthy, were the factors associated with higher odds for SA. Newly emerging aspects of increasing importance in research on SA include psychological factors and well-being.

The review confirms past research highlighting the value of a healthy lifestyle throughout the life course as a major determinant of SA (32). It essentially points to that adopting an overall healthy lifestyle rather than focusing on avoidance of risk factors seems to be the key to long-term sustained health. These findings largely correspond to the results by previous reviews (8, 15, 42). Among individual determinants, adherence to healthy dietary patterns, such as the Mediterranean diet, have been pronouncedly associated with

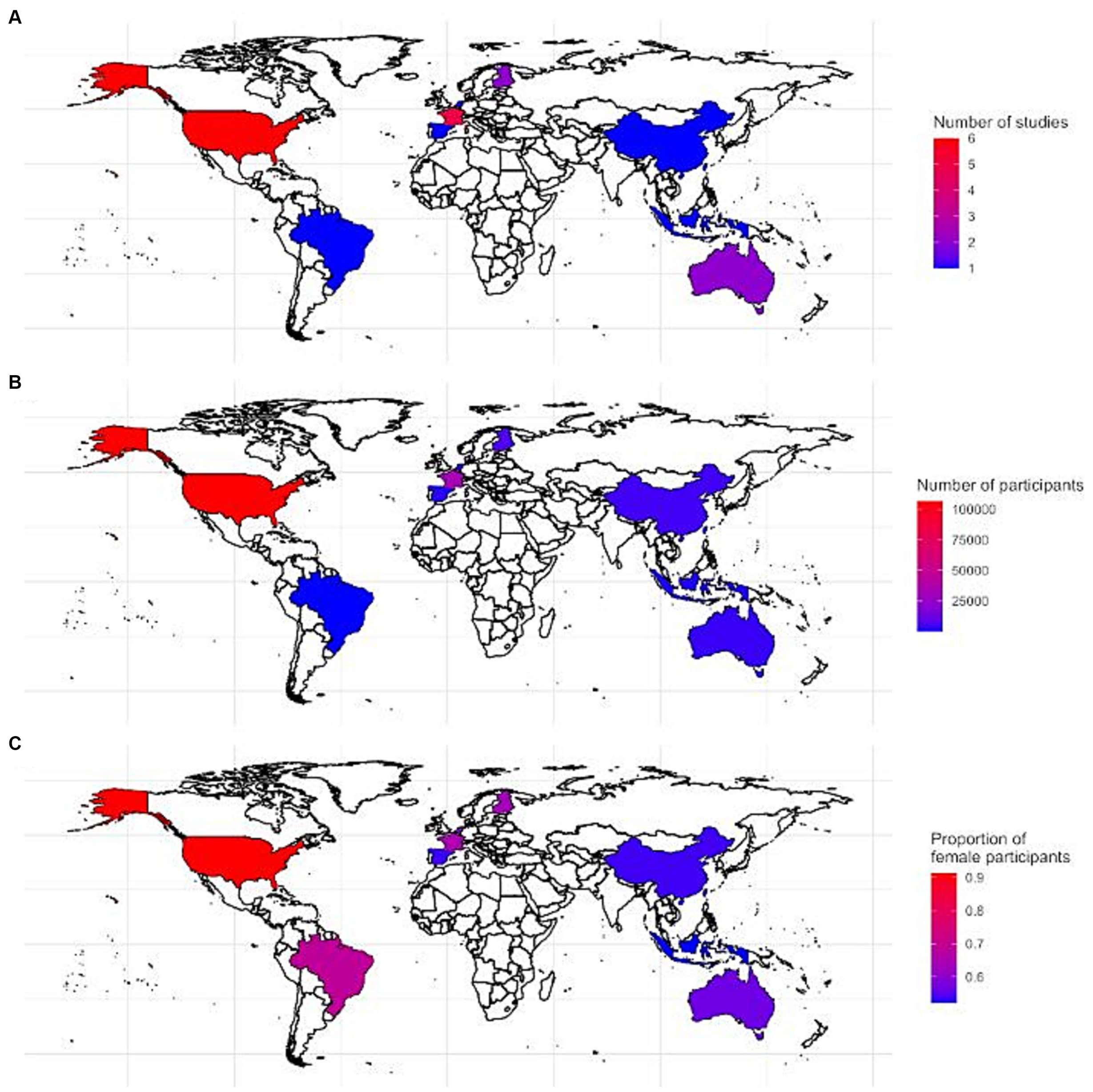

FIGURE 2
Graphical representation showing the geographical area covered by the studies in the systematic review: **(A)** the number of included studies, **(B)** the total number of participants based on the included studies, and **(C)** the proportion of females in the total amount of included participants per country.

higher chances for SA (24, 30, 31, 40). In contrast, individual dietary components, such as high carbohydrate intake and high glycaemic index of a diet were not associated with SA (39). The current review found moderation in the consumption of alcohol to be positively associated with SA, albeit in the context of following an overall healthy diet. In contrast, in previous review, Kralj et al. (15) reported mixed findings for the same association. Potential explanations for these discrepant findings could be sought in the assessment and categorization of drinking patterns among studies, the type of alcohol consumed, and the different reference categories used. Our results are in line with results from a more recent systematic review that reported that as compared to complete abstinence moderate alcohol consumption was positively associated with healthy aging (10). Furthermore, our results revealed that sleeping habits including sleeping time and quality were strongly associated with SA (22). This evidence comes in support of previous research showing that sleep is associated with improved cognitive functioning and may be protective against aging-related cognitive decline (43).

Another highlight of the current review is the role of the metabolic health as an important biological intermediate factor for SA (38). Suboptimal levels of lipid metabolism biomarkers, high blood pressure, and high glucose levels over prolonged time periods have been long known to predispose higher risk of age-related chronic diseases, including cardiovascular disease (44) and type 2 diabetes (44), as well as overall mortality, and have also been negatively associated with SA (28). Metabolic disorders are associated with chronic systemic inflammation leading to the generation of reactive oxygen species and oxidative stress that exacerbates the aging process,

TABLE 1 Summary of the baseline characteristics of included studies.

First author, year (Reference)	Study population	Country	Study period	Sample size	Baseline age (years)	Gender (%)	Socio-demographic	Nutrition and lifestyle	Metabolic health	Psychological
Aalto et al. (2023) (19)	Helsinki Aging Study	Finland	4 waves: 1989, 1999, 2009, 2019	$N_{1989} = 552$ $N_{1999} = 2,396$ $N_{2009} = 1,492$ $N_{2019} = 1,614$	≥75 years	Female: 69.0%	X			X
Zhu et al. (2023) (20)	China Health and Retirement Longitudinal Study	China	Baseline: 2013 End of follow-up: 2015	$N = 4,280$	≥60 years	Female: 53.6%	X			X
Oktaviani et al. (2022) (21)	Indonesia Family Life Survey	Indonesia	Baseline: 2007 End of follow-up: 2014	$N = 1,289$	≥60 years	Female: 52.1%	X	X		X
Lee-Bravatti et al. (2021) (22)	Boston Puerto Rican Health Study	United States	Baseline: 2004 End of follow-up: 2009	$N = 889$	≥45 years	Female: 71.4%	X	X	X	X
Lin et al. (2021) (23)	Taiwan Initiatives for Geriatric Epidemiological Research	Taiwan	Baseline: 2011 End of follow-up: 2019	$N = 467$	≥65 years	Female: 54.8%	X	X	X	X
Assmann et al. (2019) (24)	NutriNet-Santé Study	France	Baseline: 2009 End of follow-up: 2016	$N = 21,407$	≥45 years	Female: 72.8%		X		
Cooney and Curl (2019) (25)	Health and Retirement Study (HRS)	United States	Baseline: 1998 End of follow-up: 2012	$N = 12,108$	≥51 years	Female: 52.5%	X	X		
James et al. (2019) (26)	Nurses' Health Study	United States	Baseline: 2004 End of follow-up: 2012	$N = 33,326$	68 years*	All female				X
Kim et al. (2019) (27)	Health and Retirement Study (HRS)	United States	Baseline: 2006 End of follow-up: 2014	$N = 5,698$	>50 years	Female: 61.3%				X
Lassale et al. (2019) (28)	English Longitudinal Study of Aging	United Kingdom	Baseline: 1998 End of follow-up: 2012	$N = 2,437$	≥47 years	Female: 56.5%			X	
Urtamo et al. (2019) (29)	Helsinki Businessmen Study	Finland	Baseline: 1974 End of follow-up: 2010	$N = 533$	≥40 years	All male	X	X	X	
Assmann et al. (2018) (30)	NutriNet-Santé Study	France	Baseline: 1994 End of follow-up: 2007	$N = 2,249$	≥45 years	Female: 46.5%		X		
Assmann et al. (2018) (31)	SU.VI.MAX Study	France	Baseline: 1994 End of follow-up: 2007	$N = 3,012$	≥35 years	Female: 47.6%		X		
Atallah et al. (2018) (32)	SU.VI.MAX Study	France	Baseline: 1994 End of follow-up: 2009	$N = 2,203$	≥45 years	Female: 45.7%		X		

(Continued)

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TABLE 1 (Continued)

First author, year (Reference)	Study population	Country	Study period	Sample size	Baseline age (years)	Gender (%)	Socio-demographic	Nutrition and lifestyle	Metabolic health	Psychological
Domènech-Abella et al. (2018) (33)	COURAGE in Europe project	Spain	Baseline: 2011 End of follow-up: 2014	$N = 1,886$	≥50 years	Female: 53.5%	X			
Lai et al. (2018) (34)	Cardiovascular Health Study	United States	Baseline: 1992 End of follow-up: 2015	$N = 2,622$	74.4 years*	Female: 63.4%		X		
Rinaldi et al. (2018) (35)	The Porto Alegre Longitudinal Aging Study (PALA)	Brazil	Baseline: 1996 End of follow-up: 2012	$N = 210$	≥60 years	Female: 69.0%	X			X
Jaspers et al. (2017) (36)	The Rotterdam Study	The Netherlands	Baseline: 1990 End of follow-up: 2002	$N = 3,527$	≥55 years	Female: 60.2%	X			
Ma et al. (2017) (37)	Nurses' Health Study	United States	Baseline: 1980 End of follow-up: 2012	$N = 52,135$	≥33.5 years	All female		X		
Ruhunuhewa et al. (2017) (38)	SU.VI.MAX Study	France	Baseline: 1994 End of follow-up: 2009	$N = 2,733$	≥45 years	Female: 50.6%		X		
Gopinath et al. (2016) (39)	The Blue Mountains Eye Study (BMES)	Australia	Baseline: 1992 End of follow-up: 2004	$N = 1,609$	≥50 years	Female: 56.7%		X		
Gopinath et al. (2016) (40)	The Blue Mountains Eye Study (BMES)	Australia	Baseline: 1992 End of follow-up: 2002	$N = 1,609$	≥50 years	Female: 56.7%		X		

*Mean age reported only.

TABLE 2 Summary of the main results on the reported determinants of SA.

Domain	Category	Positive	Negative	Null	Mixed
Socio-demographic		↑ Occupation level (33) ↑ Household income (22, 25) ↑ Attained education (22, 25, 33) Health insurance (22)	Black or Hispanic ethnicity (22, 25) Debt (25)	Widowed or separated marital status (33) Rural residence (33) Place of residency in Southern United States (25) Age of oldest living parent (25) Never employed (33) Childhood financial adversity (25)	Female sex (21, 25, 33, 35, 36)
Nutrition and lifestyle	Anthropometrics	↓ BMI (22)	Overweight or obese, or ↑ BMI (25, 29, 38) ↑ Height (37)		
	Lifestyle	Healthy lifestyle* (32) ↑ Physical activity (19, 21, 22, 40) ↑ Quality of sleep (22)	Smoking (21, 22, 25)		
	Dietary patterns	Adherence to a healthy diet† (24, 30, 31, 40)	↑ Energy intake (40)	↑ Glycaemic index and dietary glycaemic load (39)	
	Food groups	↑ Fruit and vegetable intake (40) ↑ Fish intake (40) Medium meat intake (40) ↑ Cereal intake (40) Medium diary intake (40)	↑ Meat intake (40) ↑Biscuit and cake consumption (40) ↑ Sugar consumption (40) ↑ Non-alcoholic drinks (40)	↑ Coffee (29) Moderate alcohol consumption (29)	
	Macronutrients	↑ Fiber intake (39) ↑ n3-PUFAs intake (34) ↑ EPA levels (34) ↑ DPA levels (34)		↑ Carbohydrate intake (39) ↑ ALA levels (34) ↑ DHA levels (34)	
Metabolic Health	Biological markers		↑ CRP level trajectories‡ (28) ↑ Total cholesterol (29) ↓ Metabolic health§ (23, 38) Metabolic syndrome (23)	↑ Triglyceride levels (29) ↑ Systolic and diastolic blood pressure (29)	
Self-perceived health		↑ Self-rated health (19, 22, 29) ↑ Absence of pain that limits function (20, 24, 30–32, 36, 38)	↓ Childhood health (25)	↑ Self-rated physical fitness (29)	
Psychological		↑ Optimism (26, 27) ↑ Plans for the future (19) ↑ Feeling needed (19)			

*Healthy lifestyle defined as: healthy weight, former or never smoker, moderate to high physical activity, alcohol consumption ≤ 12 g/d for women or ≤ 24 g/d for men, and high dietary quality (32). †Healthy diet entails: adherence to guidelines of the French Nutrition and Health Program, the Literature-based Adherence Score to the Mediterranean Diet, and a modified version of the Australian diet quality index, based on the Dietary Guidelines for Australian Adults and the Australian Guide to Healthy Eating (24, 30, 31, 40). ‡The four CRP trajectories identified were as follows: "stable-low" (baseline mean CRP of 1.33 mg/L, and remaining < 3 mg/L over follow-up); "medium-to-high" (baseline mean CRP of 2.7 mg/L rising to 5.3 mg/L over follow-up); "high-to-medium" (baseline mean CRP of 6.6 mg/L, and decreasing to 2.4 mg/L over follow-up); and "stable-high" (CRP levels from 5.7 to 7.5 over the study duration) (28). §Impaired metabolic health present when corresponding to two or more of the following criteria: 1. triglycerides ≤ 1.7 mmol/L or lipid-lowering drugs; 2. systolic blood pressure ≥ 130 mm Hg, diastolic blood pressure ≥ 85 mm Hg, or use of antihypertensive drugs; 3. glucose ≥ 5.6 mmol/L or use of antidiabetic medication; 4. high-density lipoprotein cholesterol < 1.03 mmol/L for men and < 1.29 mmol/L for women (38). The arrows demonstrate whether the exposure levels associated with successful aging are low (downwards arrow, ↓) or high (upwards arrow, ↑). ALA, amino leavulinic acid; BMI, body mass index; CRP, c-reactive protein; DHA, docosahexaenoic acid; DPA, docosapentaenoic acid; EPA, eicosapentaenoic acid; N3-PUFA, omega 3 polyunsaturated fatty acids.

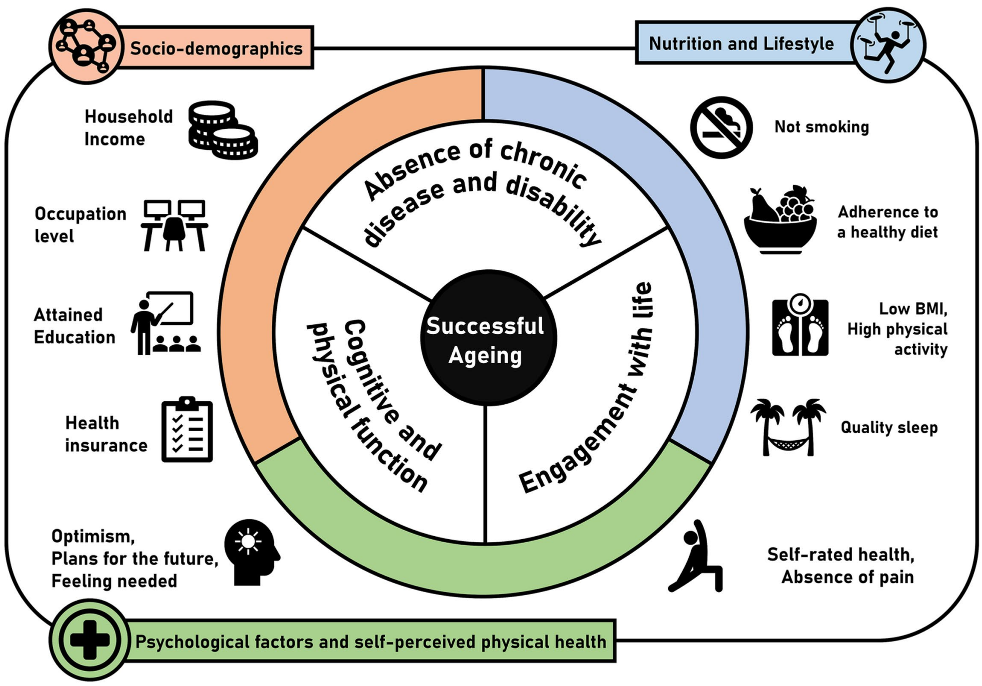

FIGURE 3
Overview of determinants and indicators of SA from the studies included in the systematic review (n = 22).

functional decline, and disease development (45–47). Additional aging phenotypes include the declining functions of the immune system, called immunosenescence, the senescence-associated secretory phenotype, shortened telomeres and decreased telomerase activity. All of these may play an important role as biological determinants for successful aging and further research would be warranted to explore relevant biomarkers associated with these processes individually and conjointly.

Our review further identified an increasing number of studies reporting on psychological factors and well-being in relation to SA. One of these factors reportedly associated with SA was optimism (26, 27). Previous research reported on the inverse association between optimism and chronic disease outcomes, incl. Cardiovascular disease, cancer, mortality, and cognitive decline (48–50). Positive life orientation may affect the adoption and maintenance of behaviors physical activity, less smoking and adherence to a healthy diet (51), which are known risk factors for cardiovascular disease. It is also plausible that optimism and pessimism affect health through biological mechanisms independent of health behaviors. Optimism has been associated with an improved immune response (52), higher levels of antioxidants in the blood (53), and advantageous high density lipoprotein cholesterol levels (54). If confirmed by future research these findings would suggest that the cultivation of optimism may be an important feature of designing strategies promoting SA. In addition, various aspects related to the socio-economic status, such as ethnicity (22, 25), marital status (33), place of residence (25, 33) and debt (25) were also found as determinants of SA. Taken together, our findings go beyond evidence provided by previous reviews, i.e., Kralj et al. (15) by extending the list of socio-economic and cognitive psycho-social factors as determinants of SA. The role of early life health assessment has been also among the newly identified factors reflecting the increased importance in research of understanding life-course determinants of health. This new evidence further underlines the notion that SA, apart from biological and lifestyle aspects, can be strongly influenced by early childhood experiences, mental health and well-being along with social justice and financial inequity.

The evidence of this review originates from well-conducted longitudinal studies, most of which were attributed a low RoB. However, the summary of results is challenging due to several methodological limitations. These include (a) the lack of a standardized definition of successful aging, (b) the large variation of methods employed for the operationalization of its multiple components, and (c) the under-representation of various population groups, particularly from less developed regions and lower socio-economic status. The results from the review should therefore be interpreted considering the differences in both measurement and definition of SA as the outcome of interest. So far, there has not been an accepted universal definition for SA and various operational definitions have been used in research (55). Next to the Rowe and Kahn's model (4), psychological models of SA have been proposed, such as the concept proposed by Baltes and Baltes (56), which puts more emphasis on the adaptation to the older stages of life and limitations to functional capacity. The model of "Aging well" by Fernandez-Ballesteros et al. (55) further includes *activities of daily living, physical and cognitive functioning, social participation and engagement*, and *positive affect and control* as additional domains within the definition of SA. Other researchers such as Young et al. (57, 58) attempted to depict further multidimensional aspects in the definition allowing assessment of SA on a continuous rather than dichotomous scale.

One of the main challenges in conceptualizing SA is combining objective criteria (e.g., functional abilities and the number of chronic

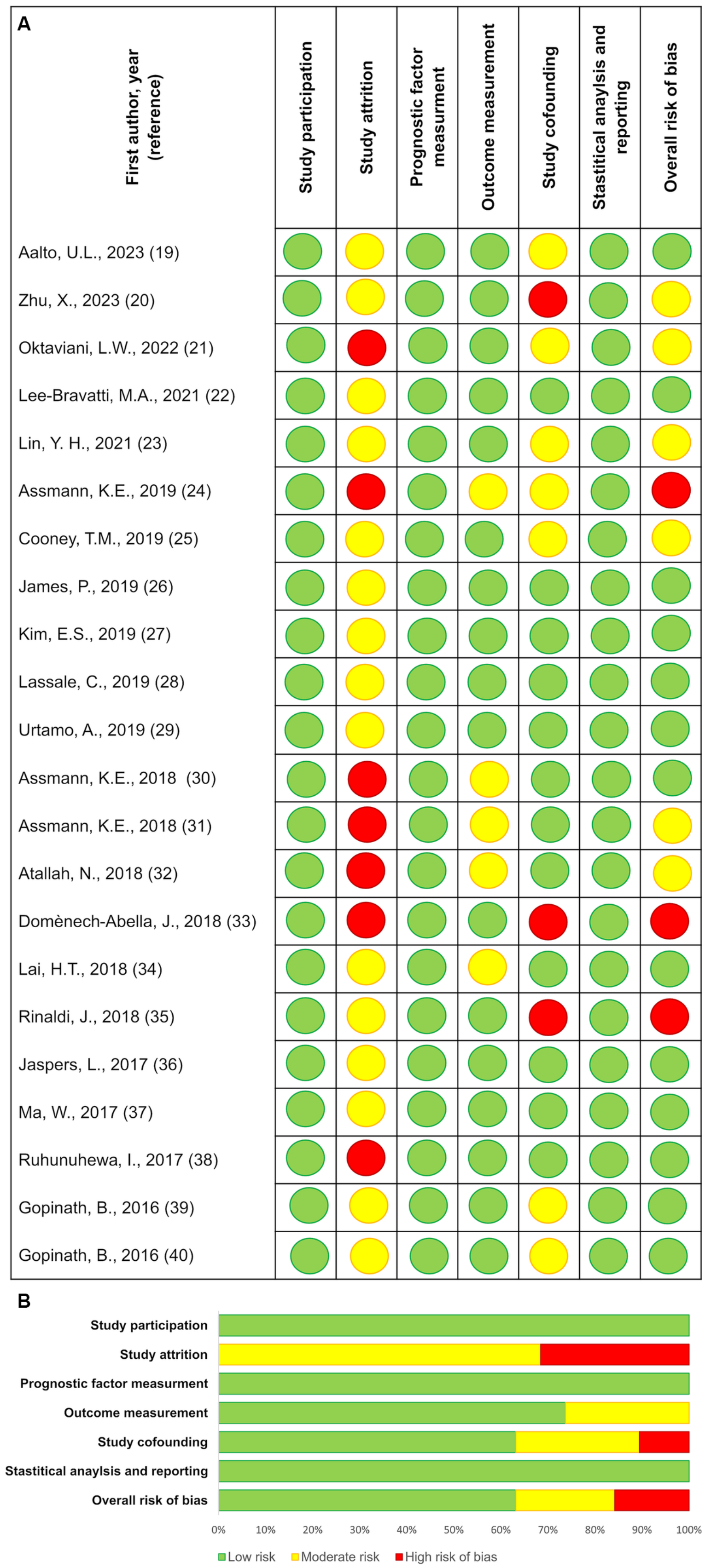

FIGURE 4
Results from the risk of bias assessments according to the Quality in Prognosis Studies (QUIPS) tool, showing ratings for the separate risk of bias domains, as well as the overall study bias. Domain 1: Study participation: to judge the risk of selection bias; Domain 2: Study attrition: to judge the risk of attrition bias; Domain 3: Prognostic factor measurement: to judge the risk of measurement bias in the measurement of the prognostic factor(s); Domain 4: Outcome measurement: to judge the risk of measurement bias in the measurement of the outcome; Domain 5: Study confounding: to judge the risk of bias due to confounding; Domain 6: Statistical analysis and reporting: to judge the risk of bias due to statistical analysis and result reporting. **(A)** Risk of bias for individual studies; **(B)** Summary risk of bias for each domain.

conditions) and subjective criteria (e.g., satisfaction with life). To combine information about objective and subjective criteria, Kok et al. (59) quantified SA according to the number of indicators in which individuals showed successful trajectories over the life course. Cosco et al. (60) created the *a priori* continuous Successful Aging Index using items identified by systematic reviews of operational definitions and lay perspectives of SA which included seven items: *maintenance of interest, absence of loneliness, optimism, self-rated health, cognitive functioning,* and *instrumental activity of daily living*. Using confirmatory factor analysis, Kleineidam et al. (61) compared five methods for assessing objective and subjective successful aging (physical health, cognitive health, disability, well-being, and social engagement) and demonstrated that these domains can be combined into a multidimensional construct. Overall, the studies included in the current review predominantly defined SA based on objective measurements of health and functionality and were less focused on a wider range of subjective criteria such as the individuals' perceptions of their own health and well-being. Recent studies showed that life satisfaction (7), purpose in life (7, 62, 63), and social engagement (14) contributed to SA and therefore should be included in operationalizing SA. Overall, more work is needed on developing a well-constructed definition for SA that balances subjective and objective aspects based on measurements of physiological health, well-being, and social engagement. Future research is warranted to provide agreed-upon operationalization of SA and standardized measurements of its separate components, to facilitate comparable findings and an adequate summary of main tendencies in research.

The strengths of the current systematic review include its actuality based on inclusion of studies published in the past 7 years, thus providing an overview of recent trends and novel findings in research on determinants and indicators of SA. Compared to previous reviews that focused on single factors, this review included a wide range of factors explored as determinants and indicators of SA. The definition of SA was carefully considered and only studies that adhered to the multidimensional concept of SA were included to allow for a better overview on the evolution of its definition and the detection of methodological gaps. The current review was conducted according to the most recent guidelines for conducting and publishing systematic reviews and included a careful assessment of study quality using predefined criteria. Furthermore, only longitudinal studies were included, which allows inferences on temporality of found associations. However, with the observational nature of the studies, causal assumptions cannot be fully supported. Most included studies proved to be of high quality, although some studies were limited by the lack of a proper evaluation of study attrition and insufficient control for potential confounding. Concerning the study attrition, it remains important to report to conduct descriptive analysis on participants that were lost to follow-up, whether they differed from the participants that completed the study, and how the study findings may thus be biased. Future studies should consider methodological limitations and provide sufficient detail on the planning and statistical analysis. The geographical coverage of the current study was also limited, with majority of studies representing populations from Europe, the United States, and Australia. Therefore, current findings may not be generalizable to populations living outside of the global north. Furthermore, the majority of studies were based on older populations which restricted the possibility to explore possible differences in studied exposures according to age group. Future studies including wider age ranges of participants, i.e., representing younger age groups, are warranted to allow a more detailed evaluation of the time and duration of exposure.

Finally, the current review aimed to depict a multidimensional definition of SA, thereby excluding studies that evaluated other age-related outcomes such as disease-free aging or healthy life-expectancy. Despite such outcomes being explored on a wider basis in epidemiology and public health research, they may not sufficiently cover additionally important aspects of the aging concept beyond absence of diseases and disability. Our work and that of previous reviews on SA as a multidimensional outcome underlines the importance of employing a holistic view to define the quality of life at older ages. Understanding the complexity of SA and subsequently fine-tuning novel approaches to address it may hold the key to adding life to years, beyond years to life.

In conclusion, this systematic review provides a summary of the recent evidence on the determinants of successful aging and highlights the importance of healthy living, monitoring metabolic risk along with sustaining mental health and well-being in adult life. Emerging research highlights the role of psycho-social factors and early life health as determinants of SA. Future research is warranted to develop a standardized definition of SA and explore the synergistic effects of its components. Investment in further methodological and research work on SA would pave the way toward development of adequate health promotion policies in aging societies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CR: Investigation, Writing – original draft, Writing – review & editing. CG: Visualization, Writing – review & editing. RA: Investigation, Writing – review & editing. MB: Writing – review & editing. KA: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1258280/full#supplementary-material

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A mito-centric view on muscle aging and function

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1 Introduction

Healthy lifestyles, such as those that include regular physical activity and a balanced diet, are a powerful means to prevent chronic disease and age-related functional decline. A common denominator of health improvements resulting from good exercise and diet habits is the optimization of metabolic processes. These processes include energy metabolism and, thus, the activity of mitochondria. Mitochondria represent hubs not only of cellular metabolism but also of the regulation of redox states, inflammatory response, and immunity, as well as many other cellular features (1). Mitochondria have emerged as highly flexible organelles that, quickly—and sometimes persistently—adapt to changing conditions in response to systemic or cellular challenges. Next to exercise and diets that promote mitochondrial health, transient exposures to environmental stressors, such as to altitude/hypoxia or extreme temperatures, also induce mitochondrial adaptations.

In this paper, we discuss how different systemic and cellular challenges trigger specific and overlapping mitochondrial responses that—under the right conditions—may translate into protective mitochondrial adaptations (2). We specifically focus on adaptations in skeletal muscle and sarcopenia, the age-related loss of skeletal muscle mass, strength, and function (3). Such responses rely on mechanisms such as mitochondrial stress responses and quality control; therefore, these mechanisms are believed to be required to maintain mitochondrial health (4). The resulting adaptations increase the capacity of mitochondria to respond to future stressors (e.g., altered oxygen or substrate availability), which otherwise might trigger pathological processes. Considering potential synergistic/anti-synergistic and complementary/competitive effects among lifestyle factors and environmental challenges on mitochondria, we argue that recommendations can be developed to increase performance, prevent sarcopenia, and improve healthy aging.

2 Mitochondrial medicine for muscle health in aging

2.1 Exercise interventions

Exercise represents a potent measure to foster healthy aging and to prevent and/or treat a large number of chronic diseases, including cardiovascular, pulmonary, neurological, metabolic, musculoskeletal diseases, and cancer (5). Those benefits, and in particular those promoted by endurance type training, are closely related to improved mitochondrial quality control (MQC, including mitophagy, the clearance of dysfunctional mitochondria), mitochondrial content, respiration, and dynamics in striated muscles (i.e., skeletal and heart muscle) (6–8). Regular exercise is thought to benefit mitochondria depending on the exercise type and intensity, although the specific determinants for mitochondrial improvements are still under debate, also due to the high diversity of exercise interventions and study populations (8, 9).

A recent systematic review reinforced the favorable effects of exercise training in older adults on mitochondrial quality, density, dynamics, oxidative, and antioxidant capacity, which varied according to the exercise type (9): While improvements of the mitochondrial antioxidant capacity appear to be important consequences of endurance exercise, resistance training seems to be particularly beneficial for mitochondrial density and dynamics.

Life-long high-volume exercise training specifically improved mitochondrial volume and network connectivity in skeletal muscle and associated oxidative capacity in older adults (10). Moreover, it preserved mitochondrial morphology, Ca^{2+} handling, and ATP production, contributing to the maintenance of skeletal muscle function in older individuals (11).

In subjects suffering from sarcopenia, more intense aerobic exercise protocols may more efficiently improve mitochondrial biogenesis (12); for example, exercise increased the mRNA levels of the mitochondrial biogenesis-related transcription factor peroxisome proliferator-activated receptor γ coactivator 1 α (*PGC-1α)* 10.2-fold at 80% of VO_2max (maximum rate of oxygen consumption), but only 3.8-fold at 40% of VO_2max (13). Low-volume high-intensity interval training (HIIT) represents a time-efficient alternative to improving skeletal muscle mass and cardiorespiratory fitness (CRF) in individuals, and even in octogenarians with co-morbidities, probably by increasing the mitochondrial oxidative phosphorylation capacity in skeletal muscle (14). Comparisons between HIIT, resistance training (RT), and the combination of HIIT and RT revealed that 12 weeks of HIIT enhanced mitochondrial content and resulted in protein changes in skeletal muscle indicative of increased mitochondrial fusion, while smaller effects were seen after combined training and (surprisingly) no effects after RT (15). These changes were associated with improved mitochondrial respiration, CRF, and insulin sensitivity in populations of untrained but lean young (18–30 years) and older (65–80 years) adults (15). Conversely, long-term RT (over 6 months) was found to considerably increase mitochondrial volume density in older individuals (16). In one recent study, 12 weeks of HIIT combined with L-citrulline supplementation increased markers of mitochondrial biogenesis, mitochondrial fusion and mitophagy in obese older adults and acted synergistically for improving muscle strength and muscle quality when compared with HIIT alone (17).

Taken together, these study findings indicate that exercise has the potential to improve or maintain mitochondrial content and health in skeletal muscle. This has been associated with healthy aging in older subjects provided that the training stimulus is appropriate, and higher intensities seeming to be more effective. Thus, it is crucial to individually tailor exercise interventions, considering individual conditions like existing diseases, exercise preferences and tolerability, training targets, as well as nutritional and supplementation strategies to support exercise-induced adaptations.

2.2 Dietary and combined interventions

The role of nutritional supplementation on sarcopenia risk and related outcomes (i.e., muscle strength, muscle mass, and performance) has been extensively summarized in previous reviews (18–21) highlighting the anti-aging potential of practicing a Mediterranean-style diet and demonstrating some evidence for the benefits of protein supplementation, especially in sarcopenic/frail older adults, when combined with RT. Frailty is a multidimensional condition that is closely related to sarcopenia (22) and mainly characterized by decreased functional reserves and stress resistance, and increased vulnerability (23). The widely used Fried frailty phenotype assesses physical frailty through five criteria: unintentional weight loss; weakness or poor handgrip strength; self-reported exhaustion; slow walking speed; and low physical activity (24).

Recently, the ProMuscle in Practice study demonstrated that increasing the amount of protein ingested per meal ($\geq$25 g) along with twice-weekly progressive RT over a 12-week intensive support intervention was effective for counteracting sarcopenia in community-dwelling older adults who were frail or pre-frail based on Fried frailty criteria or who experienced strength loss (25). The recommended daily protein intakes are 1.0–1.2 g/kg body weight (BW) for healthy older individuals and 1.2–1.5 g/kg/BW for geriatric patients, containing ∼2.5 g of leucine, to stimulate muscle protein synthesis (26). In addition, exercise and higher protein intake are recommended during weight loss, to avoid muscle wasting (27).

Caloric restriction, a lifestyle strategy to mitigate obesity and metabolic disease, which typically involves the consumption of 20–40% lower calories, shows beneficial effects on mitochondrial mass and function (28). However, this approach could also bring about unwanted reductions in lean mass, especially when the protein needs are not achieved, and may contradict dietary practices for optimizing skeletal muscle health in older persons (29). Thus, interventions to enhance the loss of fat while preserving muscle mass during energy restriction are of great importance to prevent sarcopenia in overweight older adults. Data indicate that, even in the presence of energy restriction, performance of RT with elevated daily protein ingestion (1.3 g/kg/BW) increases muscle protein synthesis and potentially supports muscle mass preservation during weight loss in obese older adults. In addition, short-term RT (over 2 weeks) stimulated mitochondrial protein synthesis as compared with energy restriction alone (30).

The few clinical trials of nutritional interventions on mitochondrial health in older healthy people or those with or at risk of malnutrition suggest that nutritional supplementation with branched-chain amino acids (BCAA) alone (31) or combined with 800 IU vitamin D3 per day (32) and omega-3 poly-unsaturated fatty acids (dosages from 3.3 to 3.9 g/day over a 4–6-month time period) (33, 34) may be useful in the prevention of sarcopenia. These strategies boost mitochondrial bioenergetic and redox capacities, potentially explaining the amelioration of muscular performance in older adults in the absence of exercise, which reflects the real-life situation of most community-dwelling older adults (18). Beta-hydroxy-beta-methylbutyrate (3 g/day), a metabolite of leucine, has been shown to concomitantly preserve muscle mass and mitochondrial gene expression in healthy older adults during 10 days of bed rest (35). Moreover, this supplementation improved mitochondrial content and dynamics over an 8-week RT rehabilitation period as compared with the placebo control (35).

Some micronutrients, such as zinc and selenium, may also contribute to mitochondrial health and reduce oxidative stress in sarcopenia, but the evidence is still too weak to promote these nutrients as treatments for sarcopenia (36).

Finally, probiotics may actively modulate the risk and progression of sarcopenia: Preclinical research findings suggest that *Lactobacillus casei* Shirota supplementation for 12 weeks enhances muscle function potentially through the gut–muscle axis via mitochondrial signaling (37, 38). Promoting a healthy gut microbiota also improves the bioavailability of dietary polyphenols. These compounds have been shown to benefit skeletal muscle cells and tissues, thus potentially representing effective components of a treatment strategy for reducing or reversing sarcopenia (39). Indeed, two studies detected improvements in mitochondrial density and oxidative phosphorylation capacity, accompanied by enhanced skeletal muscle morphology and better mobility in aged persons after 12 weeks of admission of resveratrol (500 mg/day) combined with exercise training (40, 41).

Taken together, the current evidence suggests that dietary interventions can be effective in the prevention and treatment of sarcopenia by improving various aspects of mitochondrial health. Adherence to a Mediterranean diet, which favors a high intake of proteins, fibers, and polyphenols, and nutritional supplementation with BCAA, omega-3 polyunsaturated fatty acids, and vitamin D should be considered in older adults to support exercise-induced adaptations and muscle health. Overall, it can be concluded that the combination of diet and exercise interventions due to synergistic and complementary effects may be is the most effective approach to protect mitochondria to ameliorate sarcopenia.

2.3 Altitude and hypoxia

Epidemiological studies reveal that living at moderate altitudes (1,000–2,000 m) may increase human life expectancy (42, 43). Reduced mortality from cardiovascular diseases and certain cancer types are thought to be main mediators of this effect, and they thought to be a consequence of the lower oxygen partial pressure, and thus reduced oxygen availability (hypoxia), at these altitudes (43). This hypothesis is supported by evidence that exposure to mild chronic continuous environmental hypoxia extends the lifespan of various species, including worms (44), fruit flies (45), and mice (46).

Accumulating evidence suggests that brief and repeated exposures to mild or moderate hypoxia (hypoxia conditioning, HC) also induce physiological and cellular adaptations which protect individuals from subsequent, more severe hypoxic or ischemic insults and possibly from age-related diseases (47, 48). In contrast to the potential beneficial impact on healthy aging and life expectancy conferred by exposure to mild or moderate hypoxia, exposure to more severe hypoxia may even accelerate aging, potentially due to the augmentation of oxidative stress, inflammation, and mitochondrial dysfunction (48). Thus, major health benefits from hypoxia exposure may not result from hypoxia *per se* but rather from adaptations initiated by exposures to hypoxia at appropriate intensities, durations, and frequencies (49).

Mitochondria are key to adaptations involved in the induction of cellular stress responses, the upregulation of antioxidant pathways, and the optimization and reduction of oxidative metabolism rates (4, 50). Interventional studies have revealed the preventive and therapeutic effects and promotion of healthy aging by HC by, for example, improving exercise tolerance and cognitive performance in healthy older adults or those with pre-existing cardiovascular, pulmonary (51), or age-related neurological deficits (52). For example, after 3 weeks of intermittent hypoxia, VO_2max increased by 6.2% in older men with and without coronary artery disease while no change was observed in the normoxic control (53).

Moreover, exercise training in athletes (twelve high-intensity treadmill sessions over 6 weeks, in addition to regular trainings) under normobaric hypoxic conditions (FiO_2: 14.5%, 3,000 m) increased the gene expression of the mitochondrial biogenesis regulators *PGC-1α* and *transcription factor A* and elevated mitochondrial enzyme activity (i.e., of citrate synthase and cytochrome oxidases 1 and 4) (54). A recent meta-analysis revealed greater improvements in the body fat and body mass index of middle-aged and older adults when exercise was performed under normobaric hypoxic conditions as compared to normoxic conditions (55). The authors suggest that changes in cellular energy production and mitochondrial protein synthesis may be potential mechanisms associated with modifications in body composition (55). However, whether exercising in hypoxia benefits older people more than exercising in normoxia remains to be elucidated. A recent study in sedentary older individuals found no differences in mitochondrial and functional outcomes between these modalities after 8 weeks of aerobic exercise (56).

In summary, together with exercise and dietary interventions, HC represents a promising strategy to counteract skeletal and cardiac muscle dysfunction and conditions of sarcopenia, and thus to promote healthy aging. Which HC programs optimally improve specific mitochondrial functions and muscle health remain to be identified and will need to consider individual circumstances (e.g., physical and mental performance capabilities, co-morbidities, pharmacological therapy, and responsiveness to hypoxia exposure). A selection of studies linking exercise, dietary, hypoxia and combined interventions to mitochondrial and muscle or fitness outcomes are summarized in Table 1.

3 Discussion

Increasing mitochondrial deficits (58), the associated oxidative stress (58), and inflammatory processes (59) are central processes in aging. Accordingly, mitochondrial health and the associated oxidative capacity also declines with age in skeletal muscle. This decline is correlated to reduced muscle performance and CRF (60, 61). It is thus plausible that aging mitochondria are involved in the development of age-related sarcopenia, although the specific concerned mitochondrial deficits (e.g., oxidative phosphorylation, biogenesis, dynamics, quality control) remain to be elucidated (62). Importantly, direct data on mitochondrial outcomes of lifestyle-interventions in sarcopenia are scarce and experimental confirmation on potential preventive and symptomatic benefits are urgently required.

TABLE 1 Selected lifestyle interventions targeting mitochondria in muscle aging.

Intervention and population	Mitochondrial outcomes	Muscle or fitness outcomes	References
Exercise interventions			
Four-week HIIT, ≈15 min/week (100–115% of maximal workload) in octogenarians (81.2 ± 0.6 years) with comorbidities	Improved mitochondrial oxidative phosphorylation capacity: increased activities of the mitochondrial enzymes citrate synthase and complexes II and III of the respiratory system	Increased muscle protein synthesis, cardiorespiratory fitness and fat-free mass	(14)
Twelve-week HIIT, resistance, or combined training in young (18–30 years) and older (≥65) sedentary adults	Increased mitochondrial volume and number, higher protein levels of the mitochondrial fusion factor OPA1 and improved mitochondrial respiration by HIIT	Improved cardiorespiratory fitness and fat-free mass in all training groups	(15)
Eight-week resistance, endurance or combined training in young (18–30 years) and older (≥65) sedentary adults	Improved mitochondrial respiration in combined training groups (young and older)	Combined training resulted in the most robust improvements in muscle strength, quality, and fitness	(57)
Dietary interventions			
BCAA supplementation of older malnourished patients (>80 years) for 8 weeks	Improved mitochondrial biogenesis and fusion and lower levels of oxidative stress	Improvements in nutritional status, muscle mass, strength and performance	(31)
Supplementation of older adults (>65) with/at risk of undernutrition for 12 weeks: whey and casein protein, ursolic acid, free BCAA and vitamin D	Upregulated expression of gene clusters (microarray) related to oxidative phosphorylation, mitochondrial functioning, and mitochondrial biogenesis	Improved walking performance	(32)
Omega-3 poly-unsaturated fatty acid supplementation (1.86 g/day EPA, 1.5 g/day DHA) for 6 months in older (60–85 years) adults	Small, upregulated expression of gene clusters (microarray) related to mitochondrial functions	Improved muscle mass and function	(34)
Combined exercise and dietary interventions			
Citrulline supplementation (10 g/day) and HIIT for 12 weeks in obese older (67.2 ± 5.0 years) adults vs. placebo (same exercise program)	Increased mitochondrial biogenesis, mitochondrial fusion, and mitophagy in both groups	Improved lean mass, muscle power, and function in both groups; greater increase in muscle strength and quality	(17)
Two-week energy restriction (−300 kcal/day, 1.3 g/kg/day protein) vs. energy restriction plus resistance training in obese older (66 ± 4 years) men	Increased mitochondrial and myofibrillar protein synthesis by resistance training	Preserved muscle mass during weight loss by resistance training	(30)
Beta-hydroxy-beta-methylbutyrate (3 g/day) supplementation during 8-week resistance training in 60–76 years old subjects after 10 days bed rest	Increased protein levels of oxidative phosphorylation components and of mitochondrial fusion (mitofusin 2) and fission (DRP1) factors	Preserved muscle mass	(35)
Resveratrol (500 mg/day) and combined resistance/endurance training for 12 weeks in 65–80 years old subjects vs. placebo (same exercise program)	Increased mitochondrial density, higher transcription levels of mitochondrial pro-fusion factors	Increased muscle fatigue resistance, mean fiber area and muscle torque/power	(40)
Exercise in hypoxia			
Sedentary adults (62 ± 6 years) trained 3 × per week for 8 weeks in normobaric hypoxia (15%) vs. normoxia on a bicycle ergometer	No differences in markers of mitochondrial content and oxidative capacity (activities of citrate synthase and components of the mitochondrial respiratory system)	Similar improvements in muscle metabolism (lactate, fat and carbohydrate oxidation) and in power output after hypoxic and normoxic training	(56)

BCAA, branched-chain amino acids; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; HIIT, high-intensity interval training; OPA1, optic atrophy 1.

The overlapping but also seemingly differential mitochondrial benefits of different lifestyle interventions might be harnessed to design optimized mixed lifestyle interventions that counteract the development of sarcopenia or alleviate its symptoms. These interactions among lifestyle factors and their results on mitochondrial activity, however, are still poorly known and controversially discussed. Different exercise modalities and intensities, for example, may differentially improve the mitochondrial biogenesis (resistance training, moderate endurance training) and dynamics (resistance training), antioxidant capacity (moderate endurance training), quality control/mitophagy (moderate endurance training), or oxidative phosphorylation capacity (intensive endurance training) (8, 9).

Like exercise, a mild caloric restriction and certain nutrients may help to preserve specific facets of mitochondrial health and might be suitable as a counteracting strategy for sarcopenia. These include the use of beta-hydroxy-beta-methylbutyrate supplements, which seem to effectively promote mitochondrial

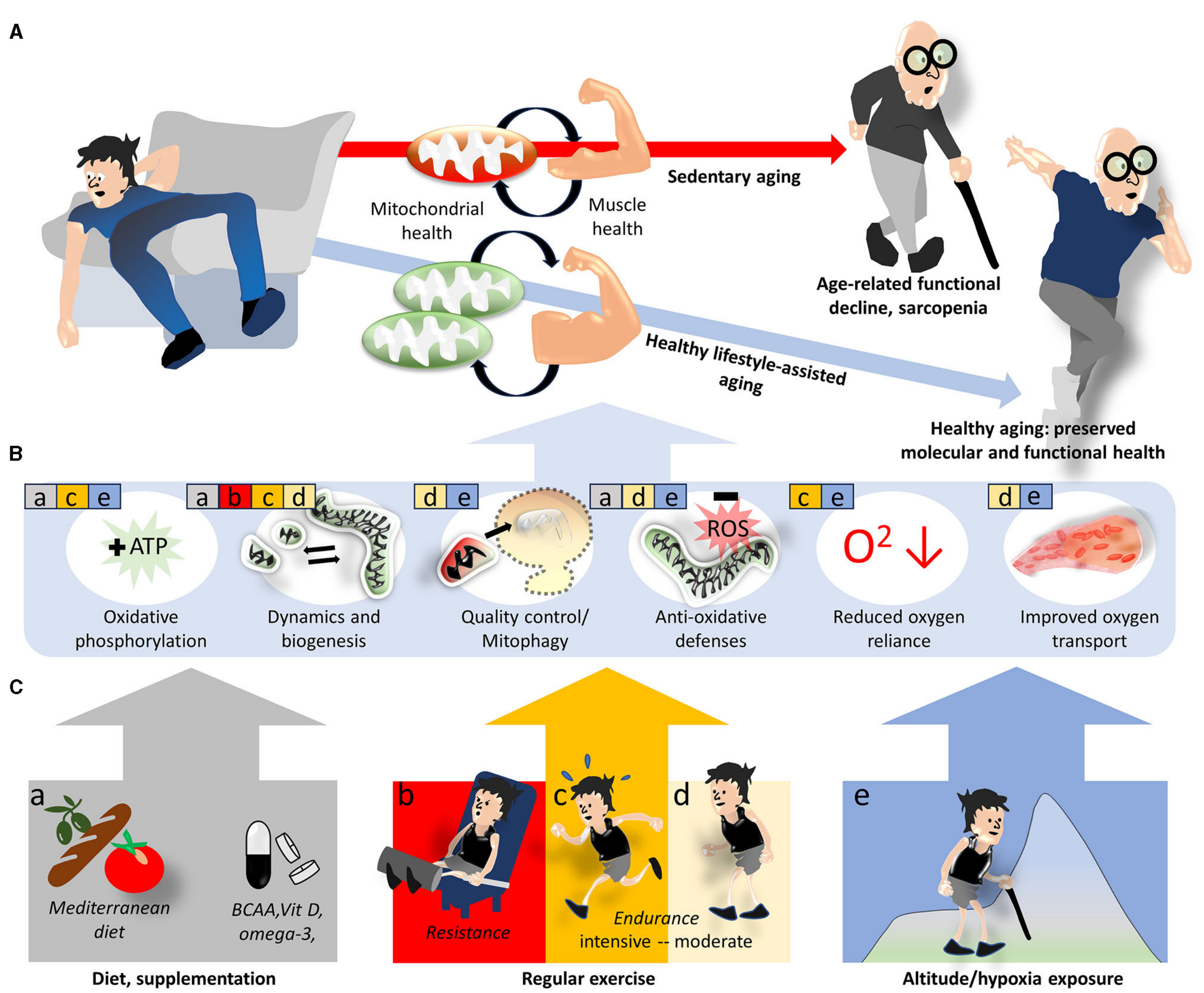

FIGURE 1
Lifestyle interventions modulating mitochondrial and skeletal muscle health to prevent sarcopenia. Sedentary aging is associated with increasing mitochondrial deficits and functional decline of skeletal muscle and favors the development of sarcopenia, while the adoption of a healthy lifestyle provides some protection **(A)**. On the molecular level, this protection is believed to be mediated by improvements in various mitochondrial functions and related oxygen utilization factors **(B)**. Specific aspects of mitochondria and oxygen utilization discussed in the text are indicated by colored squares and letters a–e in **(B)**, where the colors/letters correspond to lifestyle/environmental factors shown in **(C)**.

density and dynamics (35). In combination with exercise, resveratrol also appears to improve mitochondrial density and oxidative phosphorylation (40, 41).

The controlled variation in hypoxia levels (by climbing to different altitudes, spending time in hypoxia chambers/tents, breathing of defined gas mixtures, or performing breathing exercises) may also modulate specific mitochondrial functions, depending on the severity, duration, and frequency of the exposure (50). Cellular adaptations to hypoxia include increased oxidative phosphorylation efficiency and antioxidative capacities, but also enhanced cellular oxygen supply due to the improved oxygen transport in the blood (e.g., as a result of erythropoietin upregulation) and angiogenesis, as well as glucose transport and glycolysis upregulation, which reduce the reliance of ATP production on oxygen levels (50).To take full advantage of the potentially complementary and synergistic benefits of exercise, dietary strategies and hypoxia exposure, the distinct effects of these interventions need to be better understood (Figure 1).

Very few studies report small or no effects of higher physical activity levels and/or healthy dietary behaviors, such as Mediterranean diet, on sarcopenia prevalence [e.g., (63)], suggesting limitations of the preventive potential of healthy lifestyles.

Specifically, sarcopenic or malnourished older adults tend to develop an anabolic resistance to three fundamental anabolic stimuli [i.e., insulin signaling, BCAA (primarily leucine) blood concentration, and physical activity]. For these older people (64), individually optimized dietary protein intake combined with RT are required to maintain or improve muscular strength and mitochondrial function with aging. Physical activity, and predominantly endurance exercise, often potently counteracts sedentary aging associated with mitochondrial dysfunction, insulin resistance and obesity. But combinations with adequate dietary strategies, RT and hypoxia can further optimize mitochondrial health and muscle performance. Well-calibrated RT benefits almost all older people (65) and reduces the risk of sarcopenia in older adults adhering to aerobic moderate-to-vigorous physical activity guidelines even further (66).

Based on the high complexity of outcomes in lifestyle changes, the investigation of combined approaches (e.g., diet and exercise interventions) are challenging and individualized combinations of different training types and dietary regimes accompanied by monitoring and continuous program adaption will be important to guarantee success. Person-centered strategies are especially important for vulnerable populations to ensure exercise and/or hypoxia benefits and an appropriate nutritional status, while balancing these factors with associated risks (injury risk, oxidative stress, immune system consequences, and inflammation).

Other lifestyle and environmental factors that have not been considered in this review but may be similarly important (e.g., sleep or heat/cold acclimatization) also require further study. The complex physiological consequences of lifestyle and environmental changes also complicate efforts to compare the associated mitochondrial effects. The specific strategy outcomes, meanwhile, are determined by the application modalities (or supplement type), dose, and individual characteristics of the recipient (e.g., genetic makeup, fitness and health status). However, availability of experimental (e.g., OMICS) approaches together with increasingly powerful analytical/bioinformatic tools will pave the way for the development of a person-centered lifestyle medicine that can prevent sarcopenia and other age-related diseases.

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Exploration of the factors influencing hearing disability in older adults of China: a nested case-control study

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Objective: As two line trends – aging disability and disability aging – continue to emerge, hearing disability is becoming increasingly prevalent among older adults in china. This study aimed to investigate the incidence of hearing disability among older adults and identify the various factors contributing to its development.

Methods: In this matched nested case-control study, data from the China Health and Retirement Longitudinal Study from 2011 to 2018 were analyzed. A total of 4,523 older adults were recruited from a national sample database, of which 1,094 individuals were eligible for inclusion in the hearing disability cohort, while 3,429 older adults who had not been diagnosed with hearing disability were considered non-hearing disability controls. Hearing disability was assessed by a self-reported question. These controls were matched to hearing disability cases in a 1:1 ratio based on age and sex. The logistic regression models were used to find out various factors of hearing disability in the target population.

Results: Totally 1,094 individuals (24.14%) developed hearing disability during the follow-up period. After 1:1 matching, 2,182 subjects were included in the study, with 1,091 cases in the case group. Factors that influenced the incidence of hearing disability in older adults included annual *per capita* household income (OR = 0.985, $p = 0.003$), cognitive function (OR = 0.982, $p = 0.015$), depression level (OR = 1.027, $p < 0.001$), somatic mobility (OR = 0.946, $p = 0.007$), history of kidney disease (OR = 1.659, $p < 0.001$), history of asthma (OR = 1.527, $p = 0.008$), history of accidental injuries (OR = 1.348, $p = 0.015$), whether there is a place for recreational and fitness activities in the community (OR = 0.672, $p < 0.001$), and whether there is a health service center/health center in the community (OR = 0.882, $p = 0.006$).

Conclusion: The incidence of hearing disabilities among older adults in China is high. The protective and risk factors that contribute to the incidence of disability should be fully considered in the care of older adults.

KEYWORDS
aging, older adults, disability, hearing, nested case-control

1 Introduction

A disabled person is defined as someone who suffers from the loss or abnormality of certain tissues or functions in their psychological, physiological, or bodily structure, resulting in an inability to normally engage in certain activities. In China, persons with disabilities are categorized into six types: hearing disability, visual disability, physical disability, intellectual disability, speech disability and mental disability. Among them, hearing disability is a condition that can result in hearing loss or impairment in both ears due to various reasons, causing difficulty in perceiving sounds from the surrounding environment and speech and hindering normal language communication activities with others (1, 2). In China, hearing loss is defined as a hearing threshold that is outside the normal range, and hearing impairment is defined as a decrease in hearing due to a variety of different causes. Distinguishing between hearing loss and hearing impairment, hearing disability encompasses both.

In the second national sample survey of people with disabilities, there were 20.04 million people with hearing disabilities, accounting for 24.16% of all people with disabilities, the largest number globally (3). More importantly, older adults appear to have become the leading population with hearing disabilities in the country. The incidence of hearing disability increases exponentially with age, with approximately 12.7 percent of older adults aged 60 years and over having a hearing disability globally, increasing to 58 percent at age 90 years (4). With China's aging population exceeding 200 million and growing at a rate of about 8 million per year, about 30–60% of the older adults have varying degrees of hearing impairment, and 70–80% of the older adults over the age of 75 suffer from hearing loss (5). The first research report on the social problem of hearing loss in the older adult, "Dare to Ask Heavenly Music|Ten Questions on Hearing Health in the older adult," released at the annual launch of our 2022, shows that about one-third of old adults over the age of 65 years old in China have a hearing disability of moderate or higher, and the number rises to about one-half among old adults over the age of 75 years old (6). Therefore, hearing disability among older adults should be carefully monitored. As disability aging becomes increasingly prevalent in China, hearing disability among older adults is gaining more attention as a major health concern, potentially becoming the third most significant issue after heart disease and arthritis (7, 8). Studies have shown that hearing disability in older adults is not simply a hearing problem; hearing disability can have far-reaching effects on older adults, not only on interpersonal interactions but also on health, independence, well-being, and quality of life (9). Hearing disability is also associated with many psychological disorders, including social isolation, depression, anxiety, and cognitive impairment (10–13).

As aging with disabilities continues to progress, care for the older adult with disabilities is an inescapable issue for society, and hearing disability, as the type of disability that accounts for the largest proportion of older adults among all types of disabilities, its management and future exploration should be focused on. China has always attached great importance to disability prevention. In 2017, China issued the Regulations on Disability Prevention and Rehabilitation of Persons with Disabilities as the first national-level guiding platform for disability prevention, emphasizing the management and supervision responsibilities of governments at all levels in disability prevention and rehabilitation and building a structure covering the whole population and the whole life cycle (14). It is essential to actively prevent and treat hearing disabilities in older adults for better prevention and improve their quality of life. Furthermore, understanding the factors contributing to hearing disability in this population is fundamental to this task. However, the occurrence of hearing disability in the older adult and its influencing factors have been largely underexplored, limiting targeted prevention and effective nursing measures of this population.

To our knowledge, research on hearing disability has been limited to investigations focused on individuals, families, or communities and primarily based on small sample sizes. At the same time, the results of the current study are limited to the physiological level of factors affecting the occurrence of hearing disability in older adults, such as chronic diseases. For example, a survey conducted by Jiang Taogen et al. in Shanghai, China, reported that the factors affecting the incidence of hearing disability in old adults were senile deafness, noise and blast deafness, systemic diseases, otitis media and other factors that affect the development of hearing disability in older adults (15). However, it is now understood that hearing disability results from a combination of multiple factors and levels. The impact of other aspects, such as the social and psychological dimensions, on the occurrence of hearing disability in older adults has been neglected. Due to the limitations of the current study, it cannot be concluded that the findings fully represent the hearing disability situation of the older adult in China. In light of this, the China Health and Retirement Longitudinal Study (CHARLS, 2011–2018) was utilized to observe the occurrence of hearing disability in older adults based on a large population sample and multivariate follow-up data. Our research aims to provide future scholars with a more detailed understanding of the factors associated with the occurrence of hearing disability in older adults and to assist them in developing targeted measures to prevent hearing disability and provide precise care in this population.

2 Materials and methods

2.1 Study design

This study is a longitudinal retrospective nested case-control study.

2.2 Study participants and data source

Data for this study were obtained from the China Health and Retirement Longitudinal Study (CHARLS) database of Peking University in 2018. This survey collects microdata representative of middle-aged and older households and individuals 45 years or older in China. The national baseline survey was conducted in 2011 and covered 150 county-level units and 450 village-level units, with data collected from approximately 10,000 households and 17,000 people. These data are tracked every 2–3 years. We used the baseline data from 2011 and follow-up data from 2013, 2015, and 2018 to establish the observation cohort. We obtained free access to the data from the official CHARLS website[1] prior to the start of the study.

1 http://charls.pku.edu.cn/

2.3 Study sample

We utilized two questions for screening the study population. Hearing disability was assessed by a self-reported question (Question 1): "Do you suffer from any of the following disabilities? ① Physical disability ② Brain damage/intellectual disability ③ Blind or partially blind ④ Deaf or partially deaf ⑤ Mute or severe stuttering." People who answered "④" in question 1 were classified as self-reported disabled.

Question 2: "When were you born?" was used to identify older adults. It should be noted that the definition of older adults in this study was in accordance with the Law of the People's Republic of China on the Protection of the Rights and Interests of the Older Adults (16), which defines "older adults" as citizens who are 60 years of age or older. This legal document establishes 60 years as the age at which older adults are entitled to most social benefits and are encouraged to retire.

We totally obtained 4,523 cases. The case group consisted of any older adult who was defined as having a hearing disability during the three follow-up visits from 2013 to 2018, while those who did not develop a hearing disability until the end of the 2018 follow-up visits were categorized as controls.

We employed a 1:1 Propensity Score Matching process by setting up a random seed in the SPSS software based on the principle of highest data utilization to match the case group with the control group according to the same sex and age ± 5 years (caliper = 0.02). The resulting data were then matched. The transformation of the study sample can be seen in Figure 1.

2.4 Variables

In this study, the variables were chosen based on the Health Ecology Model, taking into consideration the availability of data from the CHARLS questionnaire. The Health Ecology Model (17) emphasizes that the health of individuals and populations is the result of the interdependence and interaction of individual factors, physical and social environmental factors, and health services, and that these factors are also interdependent and constrained, influencing the health of individuals and populations through multidimensional interactions. He categorized these factors affecting the health of individuals and groups into five layers, starting from the core layer, which includes innate biogenetic factors such as gender, age, height, weight, BMI, and other personal traits. The second layer comprises the behavioral and psychological characteristics of individuals, while the third layer represents the family layer. The fourth layer is related to living and working conditions, and the fifth layer pertains to the socio-economic, cultural, health, environmental, and policy factors at the local,

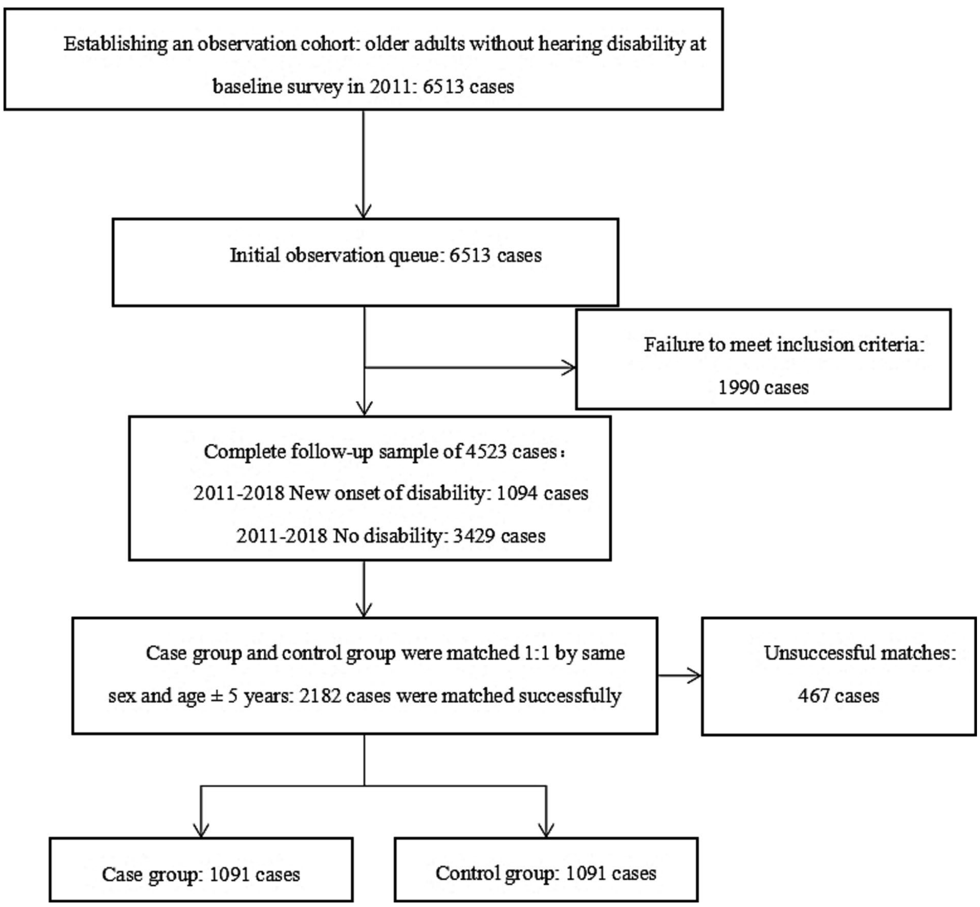

FIGURE 1
A nested case-control study sample profile of hearing disability.

national, and global levels. The research variables and their codes for this study are as follows:

1) Personal traits Personal traits include age, gender, BMI, marital status, education level, and household registration. Age was measured as a continuous variable in the original questionnaire, but we recorded age as a multicategorical variable and divided it into five categories: 1 = 60–65 years old, 2 = 66–70 years old, 3 = 71–75 years old, 4 = 76–80 years old, and 5 = 81 years old and above. Household registration, gender, and marital status are dichotomous variables (household: 1 = agricultural, 2 = non-agricultural; gender: 0 = female, 1 = male; marriage: 0 = no spouse living together, 1 = with spouse living together); BMI and education level are multicategorical variables (BMI was divided into three categories: 1 = low, 2 = normal, 3 = overweight; education level is divided into four categories: 1 = illiterate, 2 = elementary school, 3 = junior high school, 4 = high school and above).
2) Lifestyle and psychological characteristics Lifestyle and psychological characteristics included smoking, drinking, adequate sleep at night, lunch break habit, attending social events, and depression level. Adequate sleep at night and lunch break habit were dichotomous variables (adequate sleep at night: 0 = less than 6 h of sleep, 1 = more than 6 h of sleep; lunch break habit: 0 = no, 1 = yes). Smoking, drinking, and attending social events were multicategorical variables (smoking: 1 = never smoked, 2 = quit, 3 = still smoking; drinking: 1 = yes, 2 = no; attending social events: 1 = none, 2 = 1 kind, 2 = 3 kinds or more). The level of depression was measured as a continuous variable, utilizing the CESD-10 scale developed by Sirodff from the National Institute of Mental Health (18). The scale comprises ten items, and scores range from 0 to 30. Higher scores represent higher levels of depression.
3) Household level Household-level factors include annual *per capita* household income (thousand dollars), number of children, residence, and area of residence. Annual *per capita* household income is a continuous variable and is filled in with actual values. Number of children and residence were assessed as multicategorical variables (1 = no children, 2 = 1, 3 = 2 and more, residence, 1 = living with children, 2 = living in close proximity to children, 3 = living away from children). Area of residence was a dichotomous variable (1 = rural, 2 = urban).
4) Living and working conditions The living and working conditions that were considered in this study included factors such as whether the participant had barrier-free access, access to a toilet or bathing facilities, suffered from comorbidities, other disabilities, history of falls, hip fractures, cataract surgery, glaucoma, accidental injury, as well as measures of cognitive function and somatic mobility. Each factor was analyzed as a dichotomous variable, with scores of 0 representing no and scores of 1 representing yes. Comorbidities included hypertension, dyslipidemia, diabetes mellitus, malignancy tumor, chronic lung disease, liver disease, heart disease, stroke, kidney disease, digestive system disease, emotional/psychiatric disorders, memory-related disease, asthma and arthritis/rheumatism. Other disabilities encompassed visual, speech, intellectual, and physical disabilities. Cognitive function was assessed using the Mini-mental State Examination (MMSE) (18), which has 31 questions to evaluate cognition in areas of temporal orientation, memory, delayed recall, and calculation, with a score range of 0 to 31 and higher scores indicating better cognitive function. Somatic mobility was evaluated using the Short Physical Performance Battery (SPPB) (19), which includes balance, the 4 min walk test, and the sit-to-stand test, with a score range of 0 to 12. Higher scores reflected better somatic function among the older adult.
5) Environmental policy Several factors were assessed as dichotomous variables, such as whether there are organizations that assist the older adult, the sick and the disabled, whether the community or village primarily consists of dirt roads, whether there is a place for recreational and fitness activities in the community, and whether there is a health service center/health center in the community. Each variable was examined as a dichotomous variable, with scores of 0 representing no and scores of 1 representing yes, respectively. Additionally, the study looked at health insurance as a multicategorical variable, with categories including no insurance (scored as 1), urban and rural resident medical insurance (scored as 2), urban workers' health insurance (scored as 3), and public medical care or commercial insurance (scored as 4).

2.5 Statistical analysis

SPSS 22.0 software was used to perform all statistical analyses, and the following statistical methods were used for data analysis. The mean and standard deviation were used to express the measurement data, and the frequency and proportion were used to describe the count data. Mann–Whitney U and Chi-square tests were used for multi-group comparison of categorical variables. A conditional logistic regression analysis of the Cox risk regression model was used to estimate the risk of developing hearing disability in different older adults, and ratio ratios (ORs) and confidence intervals (CIs) were calculated.

In this study, a p-value less than 0.05 was statistically significant.

2.6 Ethical principles

The ethical application for the CHARLS survey was approved and updated annually by the Institutional Review Board of Peking University.

3 Results

3.1 Sample characteristics

Before data matching, the cohort included a total of 4,523 complete samples, of which 1,094 (24.14%) developed a new hearing disability during the follow-up period (Figure 2). After matching, the study included 2,182 subjects, aged between 60 and 96 years, with an average age of 67.28 ± 6.13 years. The study subjects exhibited a slight male predominance (n = 552, 50.6%). More details are provided in Table 1.

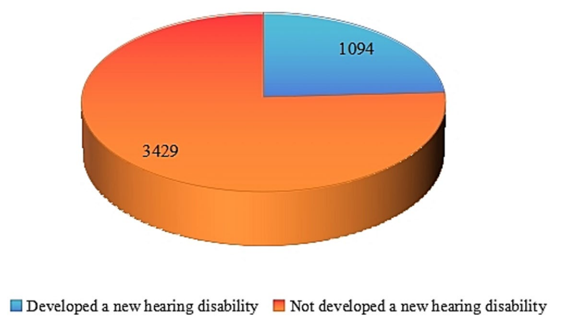

FIGURE 2
Self-reported incidence of hearing disability among older adults.

3.2 Description and correlation between the occurrence of hearing disability in older adults and other study variables

Table 1 presents the demographic characteristics that were significantly different between the two study groups, including (1) personal traits level, including education level and household registration; (2) lifestyle and psychological characteristics level, such as adequate sleep at night, attending social events, and depression level; (3) household level, including annual *per capita* household income and area of residence; (4) living and working conditions, specifically whether they have bathing facilities or not; and (5) environmental policy level, which encompasses variables such as the presence of an organization that assists the older adult, sick, and disabled, whether the community/village is primarily composed of dirt roads, the availability of recreational and fitness facilities in the community, and the presence of a health service center/health center in the community.

3.3 Indicators of factors influencing hearing disability among the older adults

The conditional logistic regression model was fitted by a Cox risk model. The study used a conditional logistic regression model to analyze the relationship between hearing disability in older adults and 23 independent variables. These variables significantly differed between the case group (those with hearing disability) and the control group (those without) during univariate analysis. More details are described in Table 1.

A stepwise analysis method was applied with an inclusion criterion of 0.05 and an exclusion criterion of 0.10. The results of the conditional logistic regression are presented in Table 2. The findings revealed that annual *per capita* household income (OR = 0.985, 95% CI = 0.975–0.995), cognitive function (OR = 0.982, 95% CI = 0.967–0.996), depression level (OR = 1.027, 95% CI = 1.015–1.039), somatic mobility (OR = 0.946, 95% CI = 0.908–0.985), history of kidney disease (OR = 1.659, 95% CI = 1.265–2.175), history of asthma (OR = 1.527, 95% CI = 1.119–2.084), history of accidental injuries (OR = 1.348, 95% CI = 1.060–1.716), whether there is a place for recreational and fitness activities in the community (OR = 0.672, 95% CI = 0.578–0.782), and whether there is a health service center/health center in the community (OR = 0.882, 95% CI = 1.075–1.528) had a statistically significant effect on the occurrence of hearing disability in older adults.

Of these factors, annual *per capita* household income, cognitive function, somatic mobility, recreational and fitness activities, and health service centers/health centers were protective factors. The risk of hearing disability decreased by 1.5, 1.8, and 5.4% for each one-thousand-dollar increase in annual *per capita* household income, cognitive function, and somatic mobility, respectively. The risk of hearing disability was also reduced by 32.8 and 11.8% for older adults with a place for recreational and fitness activities and health service centers/health centers in the community, respectively.

On the other hand, the risk of hearing disability increased by 2.7% for each unit increase in depression and by 65.9, 52.7, and 34.8% for older adults with kidney disease, asthma, and a history of accidental injury, respectively.

4 Discussion

This study was designed to conduct a nested case-control study to analyze the incidence of hearing disability among Chinese older adults and to identify the influencing factors that contribute to this phenomenon, using big data from the CHARLS database. The results showed that the incidence of hearing disability among Chinese older adults was high (24.14%), and the influencing factors included annual *per capita* household income, cognitive function, depression level, somatic mobility, history of kidney disease, history of asthma, history of accidental injuries, whether there is a place for recreational and fitness activities in the community, and whether there is a health service center/health center in the community. China has the largest older adults population in the world and is also one of the fastest-aging countries. In recent years, the Chinese government has prioritized addressing the aging population and enhancing the well-being of the older adult through policy initiatives. However, with the growing prevalence of age-related disabilities, hearing disability has become a significant health concern for older adults. Timely and targeted measures are required to prevent and treat hearing loss in old adults to promote healthy aging. The findings of this study lay the groundwork for developing effective prevention strategies for age-related hearing disability among older adults.

Our results showed that the probability of hearing disability in later life was 24.14%, significantly higher than reported in a study by Jiang et al. (15) in Songjiang, Shanghai, China (19.54%). This may be due to the wide variation in living conditions of older people across China's cities, with Shanghai being one of the most developed cities in China. Older adults in Shanghai are at a higher economic level and have access to relatively better health care and quality of life, and as a result, the incidence of hearing disability among older adults in Shanghai is lower than the national average. This also side-steps the fact that China should focus on those more underdeveloped cities, actively build public health services, and prioritize issues such as health care in difficult areas. Since the United Nations World Program of Action Concerning Disabled Persons (1983–1992) was introduced in 1983, the primary objective and focus of medicine have been to prevent disabilities and provide prompt treatment (20). Hence, it is imperative to recognize and address hearing disability in older adults in China without delay.

TABLE 1 Descriptive statistics and univariate analysis of baseline data (n = 2,182).

Variables		Case group (n = 1,091)		Control group (n = 1,091)		Statistics	p
		Frequency	Proportion (%)	Frequency	Proportion (%)		
Age (year)	60–65	363	33.3	363	33.3	0 (χ^2)	1
	66–70	297	27.2	297	27.2		
	71–75	221	20.3	221	20.3		
	76–80	113	10.4	113	10.4		
	81 and above	97	8.9	97	8.9		
Gender	Female	539	49.4	544	49.9	0.046 (χ^2)	0.830
	Male	552	50.6	547	50.1		
Household registration	Agricultural household	909	83.3	804	73.7	29.944 (χ^2)	<0.001**
	Non-agricultural household	182	16.7	287	26.3		
Area of residence	Rural	928	85.1	840	77	23.085 (χ^2)	<0.001**
	Urban	163	14.9	251	23		
Marital status	No spouse	227	20.8	233	21.4	0.099 (χ^2)	0.753
	With spouse	864	79.2	858	78.6		
Education level	Illiterate	433	39.7	390	35.7	17.690 (χ^2)	0.001**
	Elementary School	498	45.6	476	43.6		
	Junior High School	118	10.8	144	13.2		
	High School and above	42	3.8	81	7.4		
Health insurance	No insurance	77	7.1	85	7.8	24.707 (χ^2)	<0.001**
	Urban and rural residents' medical insurance	896	82.1	817	74.9		
	Urban employee medical insurance	82	7.5	128	11.7		
	Publicly funded medical insurance	19	1.7	45	4.1		
	Commercial insurance	17	1.6	16	1.5		
Annual per capita household income (thousand dollars)		5.03 ± 6.99		7.37 ± 10.57		−4.874 (Z)	<0.001**
Comorbidities	Hypertension	331	30.3	338	31	0.106 (χ^2)	0.745
	Dyslipidemia	105	9.6	97	8.9	0.349 (χ^2)	0.555
	Diabetes mellitus	71	6.5	81	7.4	0.707 (χ^2)	0.400
	Malignant tumor	7	0.6	10	0.9	0.534 (χ^2)	0.465
	Chronic lung disease	155	14.2	136	12.5	1.431 (χ^2)	0.232
	Liver disease	50	4.6	40	3.7	1.159 (χ^2)	0.282
	Heart disease	184	16.9	144	13.2	5.741 (χ^2)	0.017*
	Stroke	35	3.2	35	3.2	0 (χ^2)	1
	Kidney disease	100	9.2	60	5.5	10.791 (χ^2)	0.001**
	Digestive system disease	280	25.7	229	21	6.665 (χ^2)	0.010*
	Emotional/psychiatric disorders	14	1.3	15	1.4	0.035 (χ^2)	0.852
	Memory-related diseases	21	1.9	20	1.8	0.025 (χ^2)	0.875
	Arthritis/rheumatism	449	41.2	391	35.8	6.511(χ^2)	0.011*
	Asthma	75	6.9	38	3.5	12.777 (χ^2)	<0.001**
Suffering from other disability	Visual disability	83	7.6	68	6.2	1.601 (χ^2)	0.206
	Physical disability	50	4.6	39	3.6	1.417 (χ^2)	0.234
	Intellectual disability	30	2.7	15	1.4	5.105 (χ^2)	0.024*
	Speech disability	0	0	1	0.1	−1.000 (χ^2)	0.317
Cognitive function		9.70 ± 5.49		10.87 ± 5.64		−4.827 (Z)	<0.001**
Depression level		10.28 ± 6.87		8.32 ± 6.13		−6.661 (Z)	<0.001**
Somatic mobility		6.15 ± 1.98		6.49 ± 1.97		−3.996 (Z)	<0.001**
BMI	Low	127	11.6	113	10.4	1.891 (χ^2)	0.388
	Normal	585	53.6	572	52.4		
	Overweight	379	34.7	406	37.2		
History of disability-related illness	History of accidental Injuries (yes)	118	10.8	88	8.1	4.824 (χ^2)	0.028*
	History of falls (yes)	233	21.4	208	19.1	1.774 (χ^2)	0.183
	History of hip fracture (yes)	21	1.9	18	1.6	0.235 (χ^2)	0.628

(Continued)

TABLE 1 (Continued)

Variables		Case group (n = 1,091)		Control group (n = 1,091)		Statistics	p
		Frequency	Proportion (%)	Frequency	Proportion (%)		
	History of cataracts (yes)	40	3.7	39	3.6	0.013 (χ^2)	0.909
	History of glaucoma (yes)	24	2.2	10	0.9	5.856 (χ^2)	0.016*
Adequate sleep at night (>6 h)	Yes	408	37.4	344	31.5	8.311 (χ^2)	0.004**
	No	683	62.6	747	68.5		
Lunch break habit	Yes	495	45.4	494	45.3	0.002 (χ^2)	0.966
	No	596	54.6	597	54.7		
Attend social events	None	590	54.1	531	48.7	6.594(χ^2)	0.037*
	1 kind	356	32.6	405	37.1		
	2 kinds and more	145	13.3	155	14.2		
Smoke	Never smoked	629	57.7	642	58.8	1.447 (χ^2)	0.485
	Quit	136	12.5	118	10.8		
	Still smoking	326	29.9	331	30.3		
Drink	Yes	701	64.3	693	63.5	0.593 (χ^2)	0.743
	No	390	35.7	398	70.1		
Number of children	0	24	2.2	30	2.7	0.892 (χ^2)	0.640
	1	83	7.6	77	7.1		
	≥2	984	90.2	984	90.2		
Seeing children often	Yes	478	43.8	477	43.7	0.002 (χ^2)	0.966
	No	613	56.2	614	56.3		
Residence	Living with children	467	42.8	492	45.1	1.167 (χ^2)	0.558
	Living in close proximity to children	529	48.5	507	46.5		
	Living away from children	95	8.7	92	8.4		
Family environment	Barrier-free access	272	24.9	266	24.4	0.089 (χ^2)	0.766
	Indoor toilet available	759	69.6	794	72.8	2.736 (χ^2)	0.098
	With bathing facilities	267	24.5	351	32.2	15.929 (χ^2)	<0.001**
Community environment	Whether the community or village primarily consists of dirt roads (yes)	289	26.5	223	20.4	11.116 (χ^2)	0.001**
	Whether there is a place for recreational and fitness activities in the community (yes)	630	57.7	753	69	29.874 (χ^2)	<0.001**
	Whether there are organizations that assist the older adults, the sick and the disabled (yes)	281	25.8	356	32.6	12.471 (χ^2)	<0.001**
	Whether there is a health service center/health center in the community (yes)	861	78.9	822	75.3	3.952 (χ^2)	0.047*

N, number; M, mean; SD, standard deviation; Z, Mann–Whitney U-test; χ^2, Chi-square test. *Correlation is significant at 0.05 level; **Correlation is significant at 0.01 level.

Our study identified factors that influence the occurrence of hearing disability in older adults, which helps us to identify early and provide important interventions for those who may develop hearing disability. Ranked in descending order of importance, these factors were history of kidney disease, history of asthma, history of accidental injuries, whether there is a place for recreational and history of kidney disease, history of asthma, history of accidental injuries, whether there is a place for recreational and fitness activities in the community, whether there is a health service center/health center in the community, somatic mobility, depression level, annual *per capita* household income, and annual *per capita* household income, and cognitive function. Below we describe each of these factors in detail.

In this study, the annual *per capita* household income was a protective factor against hearing disability in older adults, implying that older adults with better household economic conditions were less likely to have hearing disabilities, consistent with the findings of a study by Fukui et al. (21) on hearing disability in Japanese people aged 36 to 84 years. However, a study by He et al. (22) in China on hearing disability in working-age adults showed no association between the incidence of hearing disability and household income, which could be attributed to the fact that the older adults population is often considered "disadvantaged" (23). In contrast with older adults, younger individuals are more resilient to general physical stresses and external trauma (24). However, aging leads to declining functional abilities among older adults (25), resulting in a greater need for medical resources and care services (26). Accordingly, families must provide more significant and better resources to older adults to sustain their well-being and quality of life, including preserving their hearing health, which places a substantial financial burden on households.

Two other protective factors against the onset of hearing disability in older adults are the availability of recreational and fitness activities in the community and somatic mobility. Somatic mobility represents

TABLE 2 Results of conditional logistic regression analysis of factors influencing hearing disability in older adults.

Variables	Regression coefficient (B)	Standard error (SE)	Wald χ^2	*p*	OR	95% CI
Annual per capita household income (thousand dollars)	−0.015	0.005	9.020	0.003	0.985	0.975–0.995
Cognitive function (scores)	−0.019	0.008	5.863	0.015	0.982	0.967–0.996
Depression level (scores)	0.027	0.006	20.425	<0.001	1.027	1.015–1.039
Somatic mobility (scores)	−0.056	0.021	7.208	0.007	0.946	0.908–0.985
History of kidney disease	0.506	0.138	13.424	<0.001	1.659	1.265–2.175
History of asthma	0.423	0.159	7.119	0.008	1.527	1.119–2.084
History of accidental Injuries	0.299	0.123	5.909	0.015	1.348	1.060–1.716
Whether there is a place for recreational and fitness activities in the community	−0.398	0.077	26.522	<0.001	0.672	0.578–0.782
Whether there is a health service center/health center in the community	0.248	0.090	7.646	0.006	0.882	1.075–1.528

$\chi^2 = 166.938$, $p < 0.001$.

the level of older adults' ability to be physically active, and the availability of recreational and fitness activities in the community represents the ability of older adults to be able to access resources for sports exercise and participation. These both imply that physical exercise and activity can aid in preventing hearing disability in older adults, consistent with the research by Martinez-Amezcua et al. (27), which revealed that hearing disability is linked to reduced physical function and walking endurance. Additionally, previous studies have indicated that moderate to severe hearing disability in older adults is associated with lower levels of physical activity (28), given that daily activities become increasingly challenging for older adults with poor physical mobility, and physical activity can lead to extra-articular involvement, including the cochlea and cochlear nerve, thereby increasing the risk of developing hearing disability (29). Therefore, to effectively reduce the occurrence of hearing disability, caregivers can develop a rationalized lifestyle exercise program for older adults to improve their overall strength and increase their physical activity.

The present study also revealed that the presence of a health service or health center in the community is also a protective factor against hearing disability in older adults. Firstly, community health facilities, to some extent, reflect the accessibility of health services, and previous research has demonstrated that access to healthcare is strongly linked to positive health outcomes in older adults (30). Besides, the availability of health centers or health homes in the community embodies the ease of access to care for older adults, enabling prompt treatment of hearing disability or other health conditions that affect hearing and reducing the likelihood of developing permanent hearing loss. Therefore, the government and community must prioritize reinforcing primary healthcare facilities to ensure that older adults have timely and comprehensive access to a wide range of healthcare services. At the same time, community workers should strengthen health screening for the older adult so that their hearing is regularly "monitored" to avoid the sudden occurrence of hearing disability.

Our study also substantiated that cognitive function is protective against hearing disability in older adults. In cognitive hearing science, it is believed that the integrity of auditory stimuli depends not only on the precise encoding of signals by functional peripheral systems but also on the decoding of stimuli by the central auditory system, which requires the involvement of higher-level cognitive processes (31). Thus, when cognitive function declines, it negatively affects the coding processes of the central auditory system, leading to an increased risk of hearing disability. Therefore, caregivers should pay attention to enhancing cognitive function in older adults so that hearing disability can be avoided to some extent. According to the recommendations of the WHO Guidelines for Community Integrated Care for Older Adults, communities should conduct regular assessments of the intrinsic abilities of older adults, with a focus on identifying at-risk populations (32). For older adults with cognitive decline, regular cognitive stimulation and cognitive training in orientation, memory, and attention are provided by caregivers and family caregivers working together to slow cognitive decline, which in turn provides a form of hearing protection for older adults.

An increasing body of evidence suggests that a decline in kidney function is linked to the development of hearing disability (33), which may explain why the presence or absence of kidney disease was a risk factor for the development of hearing disability in older adults in the present study. Thodi et al. (34) proposed that this could be due to similarities in the kidney's physiology, ultrastructure, antigens, and cochlear vascular patterns, making them vulnerable to ototoxicity caused by certain drugs and ultimately leading to hearing disability. Overall, this finding highlights the need for a comprehensive approach to preventing hearing disability in the older adult that takes into account various symptoms and focuses on maintaining overall health, developing good physical examination habits, and conducting regular assessments for early detection and prevention.

The presence of asthma is considered a risk factor for hearing disability in older adults, as previous studies have indicated a link between allergies and sudden hearing disability (35). It is highly conceivable that allergic reactions in asthma patients increase the risk of hearing disability (36), but the extent of this association is still not fully understood and requires further investigation. Nonetheless, the prevention of hearing disability in older adults should take into account the presence of asthma as a potential factor, and caregivers should be attentive when providing care for older adults with asthma. The most important thing to avoid asthma attacks is to stay away from allergens, follow the doctor's instructions for correct and continuous inhalation medication for long-term control and relief of asthma symptoms, and avoid acute attacks. Nurses are important guides for health management, and can make the older adult realize the importance of adherence to inhaled medication administration through one-on-one explanations and peer education, use video instruction and personal demonstration to make them master the correct method of medication administration, and enhance medication adherence through electronic medication monitors, telephone follow-ups and individualized intervention programs, which is conducive to the control of asthma attacks, and subsequently to avoid causing hearing damage.

Similarly, a higher incidence of hearing disability was observed in older adults with a history of accidental injuries, consistent with previous studies. For instance, blast injuries, mild traumatic brain injuries, and exposure to high-intensity or prolonged noise have been reported to increase the odds of hearing disability (37, 38). Liu et al. (39) revealed that accidental injuries in the older adult are more frequent and have serious consequences, but targeted prevention efforts tailored to different ages, genders, and injury types can significantly reduce their incidence. Therefore, the government and relevant departments should establish and improve the information monitoring system of injuries and risk factors of the older adult as soon as possible, carry out multi-level and multi-faceted interventions for the risk factors causing injuries to older adults, and continuously improve the care and aging mode of older adults, so as to minimize the occurrence of injuries from the root, and then avoid hearing problems caused by unintentional injuries.

Interestingly, our study also found that a higher level of depression was associated with an increased risk of hearing disability in older adults. This is consistent with the findings of Thomas et al. (40). This may be related to the fact that reduced activity, lack of motivation and decreased attention due to depression reduce auditory input and processing in the central auditory pathway, which subsequently leads to impaired auditory function (41). Another possible reason for this is the finding that depression may lead to hippocampal damage through the glucocorticoid cascade, allowing cognitive decline to occur in older adults, and that deterioration in cognitive function directly exacerbates hearing loss (42), which echoes our conclusions above regarding cognitive function. This suggests that nurses should maintain continuous attention to older adult people with depression. Paying attention to the psychology of the older adult and preventing depression in the older adult is an important aspect of family happiness. Nurses can encourage family members to communicate and care more about the older adult, and promote their sense of happiness (43). In addition, given the interrelationship between depression and cognitive functioning, caregivers should focus on both cognitive decline and the onset of depression rather than looking at them separately and individually.

5 Implications for public health and future research

This study revealed that the average level of hearing disability among older adults in China varies geographically, and that future exploration of national policies should focus on cities with lower overall strengths in the country, strengthen the popularization of healthcare services nationwide, and improve the average level of health of older adults nationwide. This study proved that the incidence of hearing disability should be the result of a combination of multiple factors, suggesting that the community should pay attention to older adults as a whole, and that the community should actively explore how to improve the supply of community services for older adults, design service programs that meet the physical and mental characteristics of older adults with respect to the factors associated with the incidence of hearing disability, and carry out precise services to prevent the incidence of hearing disability on a point-to-point basis. Meanwhile, given the interrelationship between depression and cognitive function, future research could explore novel programs for bidirectional interventions for depression and cognitive function in older adults, providing a comprehensive intervention approach for the prevention of hearing disability in older adults. In addition, based on the results of this study, and considering reverse thinking, delaying the development of hearing disability or even treating hearing disability by intervening in the factors associated with the development of hearing disability in older adults who have already developed hearing disability seems to be an important topic for the future.

6 Limitation

We must acknowledge the limitations of the study. First, our study of disability in older adults was derived from self-reports of older adults. While this allows for a wider sample to be included, there is a degree of discrepancy with the physician's diagnosis, which may cause some bias. Second, this study was designed to consider only one country, China, and a single population of older adults, and its main findings need to be generalized more and more cautiously to the global and disability-wide population. Third, in order to fully utilize the data in the database, this study was designed to exclude some potentially important variables with significant missing data such as the use of hearing aids, which may limit the comprehensiveness of the findings to some extent. In the end, despite the correlations between the incidence of hearing disability in older adults and various possible factors derived from our longitudinal studies, we were unable to fully explain the underlying biological mechanisms. Therefore, more in-depth experimental studies are needed to confirm these associations.

7 Conclusion

The findings of this study on hearing disability in older adults can foster the development of interventions aimed at preventing hearing disability and promoting better health outcomes. We revealed a high incidence of hearing disability among older adults in China, with various protective and risk factors identified. Protective factors included annual *per capita* household income, cognitive function, somatic mobility, availability of recreational and fitness activities, and access to health services in the community. On the other hand, risk factors included kidney disease, asthma, history of accidental injuries, and level of depression. This study provided a clear picture of the current status of disability in older adults and provided a geographical point of reference for future national policy development. The factors associated with the incidence of hearing disability in older adults identified in this study provided a target for prevention and suggested that services should be tailored to address these specific factors. To prevent hearing disability in older adults, it is essential to focus on the factors above and develop targeted measures to reduce the incidence of hearing disability in this population.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethical approval for all the CHARLS waves was granted from the Institutional Review Board at Peking University. The IRB approval number for the main household survey, including anthropometrics, is IRB00001052-11015; the IRB approval number for biomarker collection, was IRB00001052-11014. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

W-QZ: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Methodology. JL: Data curation, Methodology, Project administration, Supervision, Writing – review & editing. Y-TG: Data curation, Methodology, Project administration, Supervision, Writing – review & editing. L-SZ: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Sex-specific factors associated with acceptance of smartwatches among urban older adults: the Itabashi longitudinal study on aging

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Smartwatches (SW) are wearable devices that support daily life and monitor an individual's health and activity status. This information is utilized to promote behavior modification, which could help prevent chronic diseases and manage the health of older adults. Despite being interested in SWs, older adults tend to decrease their SW usage as they age. Therefore, understanding the acceptance of SWs among older individuals can facilitate individual health management through digital health technology. This study investigated the factors associated with the acceptance of SWs among older adults in Japan and the variations in the factors by sex. This study utilized data from the 2022 Itabashi Longitudinal Study on Aging, an ongoing cohort study conducted by the Tokyo Metropolitan Institute for Geriatrics and Gerontology. We included 899 eligible individuals aged ≥65 years. Participants were classified into three groups: possessing SW (possessor group), not possessing SW but interested in possession in the future (interest group), and not interested in possession in the future (non-interest group) using a self-administered questionnaire. The level of SW acceptance was operationally defined as follows: low (non-interest group), medium (interest group), and high (possessor group). Further, we evaluated the association of acceptance and purchase intentions of SWs with sociodemographic variables, technology literacy, and health variables. Among the participants, 4.2% possessed SWs, with no significant sex difference (men, 4.2%; women, 4.3%). Among men, age < 75 years, obesity, diabetes, and dyslipidemia were significantly associated with SW acceptance level. Contrastingly, among women, age < 75 years, living alone, higher household income, and a high score for new device use in the technology literacy category were significantly associated with SW acceptance level. Health-related factors were associated with SW acceptance in men, while technology literacy and sociodemographic factors were associated with SW acceptance in women. Our findings may inform the development of sex-specific interventions and policies for increasing SW utilization among older adults in Japan.

KEYWORDS
wearable healthcare device, mobile health, smart wearables, health promotion, technology innovativeness

1 Introduction

Smartwatches (SW) are widely recognized as wearable devices that support daily life. According to the Allied Market Research (1), the market size of SW was estimated at $206.4 billion in 2019 and is projected to reach $963.1 billion by 2027. SW are small, autonomous, and non-invasive devices that typically house an accelerometer; they can provide physiological indicators (2). Real-time health information tracking by SW provides useful information that can prompt adopting appropriate daily activities and behaviors. These benefits may help prevent diseases and promote health among older adults (3–8).

Although >60% of older adults are interested in SW, only a small proportion are actual users (9). For nonusers, the barriers to SW use can be an obstacle to promoting self-management of health (10). Therefore, elucidating factors related to SW acceptance and purchase intentions among older adults may help promote effective health management using digital health technologies.

Acceptance of SW is influenced by sex (11), race and cultural background (12). Therefore, to increase the usage of SW, sex- and race-specific analyses are needed. Moreover, sex differences in acceptance and purchase intentions of SW among older Japanese individuals remain unclear.

Therefore, we aimed to investigate the factors associated with the acceptance and purchase intentions of SWs among older adults in Japan. We also examined how those factors vary by sex.

2 Methods

2.1 Study design and participants

This cross-sectional study used data from the 2022 Itabashi Longitudinal Study on Aging, an ongoing cohort study conducted by the Tokyo Metropolitan Institute for Geriatrics and Gerontology. Itabashi is one of 23 special wards of Tokyo, Japan, with an area of 32.22 km^2, a total population of 583,608 (population density 18,113/km^2, as of 1 April 2023) and is formed from 134 districts. Within the Itabashi ward, Takashimadaira is a separate area. Due to urban planning and other factors, it has a higher aging population percentage and single older adult households than the other parts of Itabashi ward (13). The Itabashi Longitudinal Study on Aging is a comprehensive survey of individuals aged ≥65 years living in 37 districts of the Itabashi ward, including the Takashimadaira area.

A random mail survey was conducted among 10,812 residents in the designated areas, resulting in 3,897 respondents who were subsequently invited to participate in an on-site field survey. From this group, 1,143 individuals participated in the field survey. Among the participants, 162 individuals were excluded due to difficulties in activities of daily living ($n=7$), a Mini-Mental State Examination (MMSE) score < 23 ($n=95$), and a dementia diagnosis ($n=60$). Additionally, 82 individuals were excluded due to missing data. Ultimately, 899 individuals were included (Figure 1).

2.2 Possession of SW and purchase intentions among non-possessors

We assessed the possession of SW and purchase intentions among non-possessors. Specifically, the following questions were asked: "Do you have a smartwatch? If not, would you like to have one in the future?" Responses were categorized into three groups: "I have one" (possessor group), "I do not have one but would like to have one in the future" (interest group), and "I do not have one and do not want to have either in the future" (non-interest group) (Figure 2). The level of SW acceptance was operationally defined as follows: low (non-interest group), medium (interest group), and high (possessor group). Further, purchase intentions were categorized as low (non-interest group), and high (interest group).

2.3 Factors related to the level of acceptance and purchase intentions in SW

Based on a previous research model for wearable device use among older adults (14), we examined categories related to interest in SW, including socio-demographics, technology literacy, and health variables. The sociodemographic characteristics included age, education, employment status, household income, and cohabitation status. Technology literacy refers to the ability to use new devices to obtain information for life management. The technology literacy section of the survey also comprised social participation and interaction opportunities that influence the acceptance of wearable devices (15). Health variables were assessed based on lifestyle (physical activity, dietary diversity, and sleep quality), obesity and chronic diseases (high blood pressure, diabetes, and dyslipidemia), general health status (subjective health status, mild cognitive decline, and depressive symptoms), and the walking speed test.

2.4 Socio-demographics

Age was dichotomized using a threshold of 75 years. Education was categorized into high school or lower, junior college or vocational school, college or higher, and other options, with high school or lower being the threshold. Employment status was categorized into full-time (working ≥35 h per week), part-time (working <35 h per week), and unemployed, with employed or

Abbreviations: SW, Smartwatches; MMSE, Mini-Mental State Examination; JST-IC, Japan Science and Technology Agency's Index of Competence; PSQI-J, Japanese version of the Pittsburgh Sleep Quality Index.

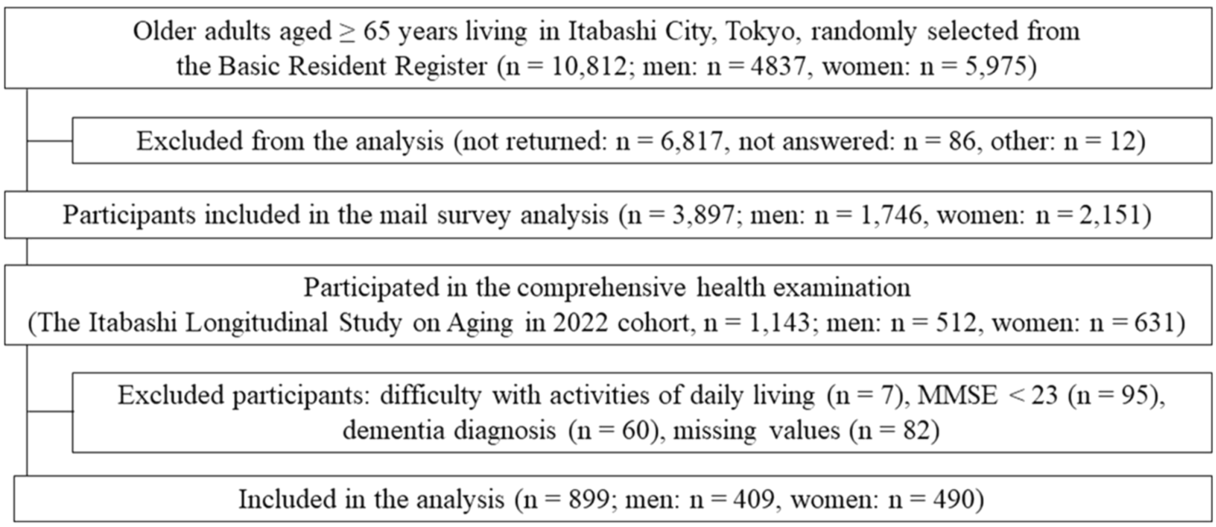

FIGURE 1
Study flowchart.

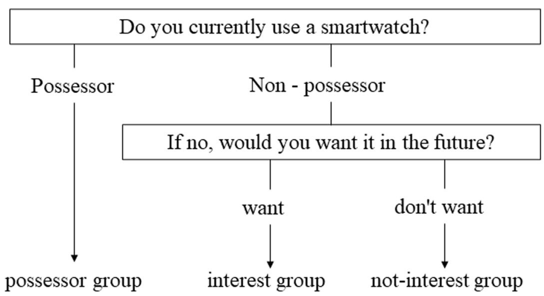

FIGURE 2
Flow of smartwatch acceptance and willingness to purchase.

unemployed being the thresholds. Household income (JPY) was categorized as follows: no income; < 1 million; 1–3 million; 3–7 million; 7–10 million; and ≥ 10 million. Previous studies reported that the top 9.7% of older households have household incomes above $75 K or more and that SW ownership is higher in this group (14). In this study, we used JPY 7 million (Approximately $50 K at the current exchange rate), the upper tier of household income similar to previous studies, as the reference value and divided it into two values: ≥ 7 million and < 7 million yen (16). Cohabitation status was dichotomized as living alone or not.

2.5 Technology literacy

Wel used the Japan Science and Technology Agency's Index of Competence (JST–IC), which assesses the ability of older adults to live independently or engage in proactive activities (17, 18). Technology literacy was assessed in terms of the following areas: technology usage (ability to use technology equipment), information practice (ability to gather information on health, literacy, and public interest), life management (ability to manage one's own and family's life and expenses), and social engagement (represents the level of interest in community or volunteer activities). The JST–IC score ranges from 0–18, with a higher score indicating more engagement. The participants were asked about socializing opportunities: "How often do you meet or go out with friends or neighbors?" Responses were categorized as less than once a month or never and once a month or more.

2.6 Health variables

Physical activity was determined by responses to questions about the frequency of participation in (1) walking/light exercise and (2) regular exercise/sports during the week: daily, at least 5–6 days/week, at least 2–4 days/week, at least once/less than once/week, or no exercise at all. The criterion for physical inactivity was both answers were 'less than once/week' for (1) walking/light exercise and (2) regular exercise/sports, otherwise 'physically active' (19).

Dietary diversity was assessed using the Dietary Variety Score (20) based on 10 food items: meat, fish/shellfish, eggs, milk, soybean products, green/yellow vegetables, potatoes, fruit, seaweed, and fats/oils. One point was assigned in case of an affirmative response to eating a food item "almost every day"; otherwise, zero points were assigned. The total score ranged from 0 to 10, with scores ≥7 considered high (21).

Sleep quality was measured using the Japanese version of the 18-item Pittsburgh Sleep Quality Index (22, 23), with a score of ≥6 indicating poor sleep quality.

Obesity was indicated by a body mass index ≥25 based on the Japanese guidelines (24). The history of chronic diseases (high blood pressure, diabetes, and dyslipidemia) was assessed through interviews conducted by experienced nurses.

Subjective health status was assessed using the following question: "Generally, which of the following phrases best describes your health?"

Responses were categorized as "very healthy," "healthy," "fair," "unhealthy," and "very unhealthy," with "very healthy" and "healthy" indicating good health.

Cognitive decline was assessed based on the MMSE (25), with a scores <27 indicating a mild cognitive decline.

Depressive symptoms were assessed using the 15-item Japanese version of the Geriatric Depression Scale (26, 27), with scores ≥5 indicating the presence of depressive symptoms.

The 5-m walking test was performed at a normal walking speed in an 11-m walking course, which comprised a 5-m measurement section sandwiched by two 3-m preliminary courses (28). The walking time (in seconds) in the 5-m measurement section was measured using a stopwatch. Walking speed was calculated by dividing the distance in the 5-m section by the walking time, with a threshold walking speed of 1.0 m/s.

2.7 Statistical analysis

We described participant characteristics according to the possessor group, interest group, and non-interest group. A chi-square test was used to analyze sex differences in the possessors (possessor group and non-possessors: a total of interest and non-interest group) and willingness to purchase (interest and non-interest group). To clarify factors related to level of acceptance in SW, we conducted ordinal logistic regression analyses, with to level of acceptance in SW as the dependent variable and demographics, technology literacy, and health variables as the explanatory variables. We adjusted for the region ("Takashimadaira area" and "outside Takashimadaira area") as a confounding variable. Additionally, we conducted binomial logistic regression analyses for interest and non-interest groups to examine intentions for purchasing SW among non-possessors. All results are presented as the adjusted odds ratio and 95% confidence intervals. Statistical significance was set at $p < 0.05$. Statistical analyses were performed using SPSS version 28.0 (IBM Corp., Armonk, NY, United States).

3 Results

3.1 Characteristics

The mean age of the included older adults was 77.7 ± 5.0 years; 54.5% of the participants were women. There were 38 (4.2%) SW possessors (Table 1). Among 861 (95.8%) non-possessors, 193 (21.5%) participants were in the interest groups. Additionally, the interest group had a higher proportion of women (25.2%) than men (19.1%) ($p = 0.035$). However, there was no significant between-sex difference in the proportion of SW possessors (men, 4.2%; women, 4.3%; $p = 0.924$).

3.2 Level of acceptance in SW

Table 2 summarizes the factors related to SW acceptance. Overall, the level of acceptance of SW was significantly associated with younger age (< 75 years), diabetes, and high scores for new device use and gathering information. Among men, younger age, obesity, diabetes, and dyslipidemia were significantly associated with SW acceptance. Contrastingly, among women, younger age, living alone, a high score for new device use was significantly associated with SW acceptance. Household income of <7 million yen for men and ≥ 7 million yen for women were associated with higher levels of SW acceptance.

3.3 Purchase intention for SW among non-possessors

Table 3 summarizes the factors related to purchase intentions for SW among non-possessors. In the overall population, younger age, diabetes, and high scores for new device use and gathering information were associated with high purchase intentions for SW. Among men, younger age, a household income <7 million yen, obesity, diabetes, and dyslipidemia were associated with high purchase intentions. In contrast, living alone and high scores for new device use and gathering information were associated with high purchase intentions among women.

4 Discussion

In the overall population, age, intellectual tasks, intellectual curiosity of technology literacy, and diabetes were associated with SW acceptance. Among men, health variables such as obesity, diabetes, and dyslipidemia were associated with SW acceptance. Contrastingly, demographic factors such as the ability to use technology, living alone, and household income were associated with high acceptance among women. In both sexes, age < 75 years was related to a high level of SW acceptance. Regarding purchase intentions, a similar trend was observed for men. However, among women, age or household income were not related to purchase intentions; instead, a high score for information-gathering skills was a factor in purchase intentions. Taken together, sex-specific interventions are warranted to increase acceptance and purchase intentions for SW.

4.1 The proportion of SW possessors among older adult individuals in Japan

Previous research suggests that the proportion of SW ownership is significantly lower among older adults than among younger individuals (29). Surveys exclusively on older populations in the United States and Canada found ownership proportions of 17.5% (14) and 12.3% (30), respectively. Also, women have a higher usage of wearable devices than men (14). Our study addressed the lack of detailed data on the SW ownership prevalence among the older population in Japan. The proportion of SW possession among older Japanese adults in the present study was 4.2%, with no sex differences, and this number was significantly lower than that reported in previous studies. Furthermore, we found a clear inverse relationship between aging and SW acceptance, with the tendency to accept SW decreasing with age. The widespread use of SW may facilitate older adults in Japan to promote their good health.

TABLE 1 Characteristics of the participants according to interest in SW.

	Total	Possessors	Non-Possessors (*n* = 861)	
			Interest	Non-interest
	(*n* = 899)	(*n* = 38)	(*n* = 193)	(*n* = 668)
Socio-demographics				
Sex				
Men	409 (45.5)	17 (4.2)	75 (18.3)	317 (77.5)
Women	490 (54.5)	21 (4.3)	118(24.1)	351 (71.6)
Age, < 75 years	283 (31.5)	18 (47.4)	76 (39.4)	189 (28.3)
Education, graduation				
Less than high school	799 (88.9)	37 (97.4)	172 (89.1)	590 (88.3)
At least junior college/ college	100 (11.1)	1 (2.6)	21 (10.9)	78 (11.7)
Employment status, employed	254 (28.3)	16 (42.1)	59 (30.6)	179 (26.8)
Household income (JPY), ≥7 mill	73 (8.1)	7 (18.4)	10 (5.2)	56 (8.4)
Living alone	325 (36.2)	12 (31.6)	84 (43.5)	229 (34.3)
Technology literacy				
Intellectual tasks (JST-IC), score	3.5 (0.9)	3.8 (0.4)	3.6 (0.8)	3.4 (1.0)
Intellectual curiosity (JST-IC), score	3.5 (0.9)	3.5 (0.9)	3.7 (0.7)	3.4 (0.9)
Information gathering (JST-IC), score	2.9 (1.1)	2.8 (1.1)	3.0 (1.0)	2.9 (1.1)
Creativity (JST-IC), score	1.3 (1.4)	1.3 (1.4)	1.4 (1.4)	1.2 (1.4)
Opportunity to socialize (≥1 wks)	552 (58.1)	28 (73.7)	112 (58.0)	382 (57.2)
Health variables				
Physical activity (≥1 wks)	716 (79.8)	31 (81.6)	155 (80.3)	530 (79.3)
Dietary variety (< 5 pts)	362 (40.3)	14 (36.8)	83 (43.0)	265 (39.7)
Sleep quality (PSQI-J score ≥ 6 pts)	595 (66.2)	26 (68.4)	133 (68.9)	436 (65.3)
Obesity (body mass index ≥25 kg/m^2)	228 (25.4)	13 (34.2)	55 (28.5)	160 (24.0)
High blood pressure, yes	474 (52.7)	21 (55.3)	90 (46.6)	363(54.3)
Diabetes, yes	121 (13.5)	3 (7.9)	36 (18.7)	82 (12.3)
Dyslipidemia, yes	207 (23.0)	5 (13.2)	49 (25.4)	153 (22.9)
Subjective health, healthy	437 (48.6)	22 (57.9)	96 (49.7)	319 (47.8)
Mild cognitive decline (MMSE <27)	338 (37.6)	10 (26.3)	69 (35.8)	259 (38.8)
Depression (GDS-15 ≥ 5 pts)	292 (32.5)	13 (34.2)	61 (31.6)	218 (32.6)
5-m walking speed test, <1.0 m/s	53 (5.9)	2 (5.3)	5 (2.6)	46 (6.9)

Data are presented as mean (SD) or *n* (%). JST-IC, Japan Science and Technology Agency Index of Competence; GDS, Japanese version of the Geriatric Depression Scale; PSQI-J, Japanese version of the Pittsburgh Sleep Quality Index.

4.2 Sex differences in factors related to SW acceptance

Older adults classified as overweight are more likely to adopt wearable devices (14). Our study further shows that those with obesity and various chronic diseases had a higher SW acceptance, a trend observed predominantly among men. Women are reportedly more interested in health-related information than men and are more attentive to how the products they purchase affect their health (31).

This increased awareness may explain why obesity and chronic diseases, such as diabetes and dyslipidemia, are more strongly correlated with SW acceptance among men. Older adults with chronic diseases are likely to access health information through smartphone apps and the Internet (32). Therefore, equipping SW with features that provide specific guidelines and goal setting for activities and sleep could make these devices particularly beneficial for men in preventing chronic conditions.

Among women, the ability to use new devices, living alone, and high household income were associated with SW acceptance. Older people often struggle with technology anxiety and resistance to change, which hinders their learning and use of digital technology (33, 34). This issue may be particularly pronounced among older Japanese women. Use of wearable devices requires regular support and feedback from healthcare professionals (35). Therefore, to reduce resistance to digital device, it is necessary to develop simple device to operate and establish a unified support system.

Women tend to use wearable devices more regularly than men to monitor their health-related information (36). Moreover, even those who do not own wearable devices have a notable interest in these devices as viable tools for improving physical and mental health (9).

TABLE 2 Sex differences in factors related to level of acceptance in smartwatches.

	Total		Men		Women	
	Crude	Adjusted*	Crude	Adjusted*	Crude	Adjusted*
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Socio-demographics						
Age, < 75 years (vs. ≥ 75 years)	1.78 (1.31, 2.43)	1.76 (1.25, 2.49)	1.91 (1.19, 3.07)	2.11 (1.21, 3.69)	1.73 (1.15, 2.61)	1.69 (1.05, 2.71)
Education, ≥ (junior) college graduate, (vs. no)	1.30 (0.79, 2.14)	1.01 (0.58, 1.74)	1.39 (0.64, 3.00)	1.06 (0.44, 2.55)	1.31 (0.66, 2.59)	0.94 (0.45, 1.97)
Employment status, yes (vs. no)	1.37 (0.99, 1.89)	1.13 (0.79, 1.62)	1.68 (1.05, 2.69)	1.43 (0.84, 2.45)	1.27 (0.80, 2.00)	0.92 (0.55, 1.56)
Household income (JPY), ≥ 7 mill (vs. < 7 mill)	0.95 (0.55, 1.65)	0.80 (0.44, 1.45)	0.44 (0.17, 1.12)	0.22 (0.08, 0.61)	2.09 (0.99, 4.38)	2.54 (1.13, 5.71)
Cohabitation status, alone (vs. others)	1.31 (0.96, 1.77)	1.31 (0.93, 1.86)	0.97 (0.56, 1.67)	0.70 (0.37, 1.33)	1.41 (0.95, 2.08)	1.98 (1.23, 3.18)
Technology literacy						
Intellectual tasks (JST-IC), score	1.51 (1.23, 1.86)	1.36 (1.09, 1.70)	1.43 (1.01, 2.03)	1.28 (0.86, 1.89)	1.62 (1.25, 2.09)	1.50 (1.13, 1.98)
Intellectual curiosity (JST-IC), score	1.44 (1.17, 1.76)	1.31 (1.05, 1.64)	1.47 (1.07, 2.02)	1.40 (0.99, 1.99)	1.40 (1.07, 1.83)	1.18 (0.88, 1.59)
Information gathering (JST-IC), score	1.13 (0.98, 1.30)	0.99 (0.83, 1.17)	1.04 (0.84, 1.29)	0.87 (0.67, 1.13)	1.20 (0.99, 1.46)	1.14 (0.89, 1.46)
Creativity (JST-IC), score	1.10 (0.99, 1.21)	1.09 (0.97, 1.23)	1.15 (0.99, 1.34)	1.14 (0.94, 1.39)	1.06 (0.92, 1.22)	1.05 (0.89, 1.24)
Opportunity to socialize (≥1 wks)	1.17 (0.87, 1.59)	1.00 (0.71, 1.40)	1.31 (0.82, 2.08)	1.09 (0.62, 1.91)	0.99 (0.66, 1.49)	0.85 (0.54, 1.36)
Health variables						
Physical activity, score	1.06 (0.73, 1.54)	0.94 (0.63, 1.41)	1.26 (0.72, 2.21)	1.09 (0.58, 2.06)	0.88 (0.53, 1.45)	0.68 (0.39, 1.18)
Good dietary variety (vs. bad)	1.09 (0.80, 1.47)	1.02 (0.67, 1.53)	1.02 (0.61, 1.70)	1.25 (0.62, 2.51)	1.02 (0.69, 1.51)	0.84 (0.49, 1.43)
Sleep quality, no (vs. yes)	0.85 (0.62, 1.17)	0.76 (0.55, 1.06)	1.09 (0.67, 1.76)	0.79 (0.47, 1.34)	0.72 (0.47, 1.11)	0.70 (0.44, 1.10)
Obesity (vs. non-obesity)	1.33 (0.95, 1.85)	1.36 (0.96, 1.93)	1.80 (1.12, 2.89)	2.07 (1.24, 3.45)	1.12 (0.68, 1.83)	1.02 (0.59, 1.75)
High blood pressure, yes (vs. no)	0.79 (0.59, 1.06)	1.02 (0.67, 1.55)	0.78 (0.49, 1.24)	1.14 (0.56, 2.32)	0.84 (0.57, 1.24)	1.10 (0.64, 1.91)
Diabetes, yes (vs. no)	1.38 (0.91, 2.08)	1.59 (1.03, 2.44)	1.44 (0.75, 2.75)	2.10 (1.02, 4.30)	1.32 (0.77, 2.26)	1.33 (0.75, 2.35)
Dyslipidemia, yes (vs. no)	0.99 (0.69, 1.40)	0.99 (0.69, 1.44)	1.47 (0.87, 2.50)	1.89 (1.05, 3.40)	0.72 (0.45, 1.16)	0.63 (0.38, 1.05)
Subjective health (vs. unhealthy)	1.16 (0.86, 1.56)	0.99 (0.72, 1.37)	1.46 (0.92, 2.33)	1.30 (0.78, 2.18)	1.002 (0.68, 1.48)	0.84 (0.54, 1.30)
Mild cognitive declines, yes (vs. no)	0.81 (0.59, 1.10)	1.06 (0.71, 1.56)	0.62 (0.38, 1.01)	0.86 (0.47, 1.57)	1.02 (0.68, 1.55)	1.28 (0.75, 2.19)
Depression symptoms, no (vs. yes)	1.03 (0.75, 1.41)	1.09 (0.78, 1.51)	0.91 (0.56, 1.48)	1.14 (0.67, 1.96)	1.04 (0.69, 1.59)	1.05 (0.67, 1.65)
5-m walking speed test, <1.0 m/s (vs. ≥1.0 m/s)	2.31 (1.04, 5.16)	2.04 (0.89, 4.67)	1.61 (0.54, 4.76)	1.92 (0.59, 6.22)	3.24 (0.97, 10.8)	2.52 (0.73, 8.74)

OR, odds ratio; CI, confidence interval; JST-IC, Japan Science and Technology Agency Index of Competence. *Region.

Interestingly, contrary to the findings of this study, the use of wearable devices in Finland was higher among married or cohabiting older people than among their single counterparts (37). Among older Japanese women, increased health-related anxieties due to living alone may increase their interest in self-health management, potentially leading to higher acceptance of SW.

4.3 Sex differences in the purchase intentions for SW

SW purchase intention among men in Japan was associated with high scores for social engagement in addition to SW acceptance-related items. Opportunities for social participation and interaction are believed to influence the acceptance of SW (38). Older men may be more dependent on peers and family members regarding SW implementation. Thus, social campaigns about SW with family and friends using opportunities for social participation and interaction may lead to SW adoption.

Among women, the use of new equipment was associated with the ability to gather information, but not with social participation. This finding suggests that women may be more influenced by information about SW from information technology devices (e.g., Internet, smartphones, TV) than by social participation. Therefore, featuring SW on TV or other media in connection with health may increase their willingness to purchase SW. In contrast, household income above JPY 7 million was associated with higher SW acceptance among women but not with purchase intention. Women prefer lower-priced SW than men (39). However, women may not be aware of the price of SW at the stage of purchase intention. In our survey, women were more likely than men to have a high purchase intention, but no significant difference was observed in the percentage of ownership. This may be due to the high price of SW. Therefore, it is desirable to investigate the price range of SW desired by older adult women in Japan.

This study has several limitations. First, we only used data from Japanese participants and only one urban region, limiting the

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TABLE 3 Sex differences in the purchase intentions for smartwatches.

	Total		Men		Women	
	Crude	Adjusted*	Crude	Adjusted*	Crude	Adjusted*
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Socio-demographics						
Age, < 75 years (vs. ≥ 75 years)	1.68 (1.20, 2.34)	1.78 (1.22, 2.59)	2.01 (1.20, 3.36)	2.57 (1.38, 4.80)	1.52 (0.97, 2.36)	1.52 (0.91, 2.55)
Education, ≥ (junior) college graduate, (vs. no)	1.14 (0.68, 1.92)	0.83 (0.48, 1.46)	1.06 (0.49, 2.28)	0.80 (0.33, 1.94)	1.18 (0.59, 2.40)	0.82 (0.38, 1.79)
Employment status, yes (vs. no)	1.23 (0.87, 1.75)	1.07 (0.72, 1.59)	1.53 (0.92, 2.56)	1.36 (0.75, 2.49)	0.83 (0.51, 1.36)	0.88 (0.50, 1.57)
Household income (JPY), ≥ 7 mill (vs. < 7 mill)	0.60 (0.30, 1.19)	0.51 (0.25, 1.07)	0.20 (0.05, 0.83)	0.09 (0.02, 0.42)	1.42 (0.60, 3.39)	1.78 (0.69, 4.55)
Cohabitation status, alone (vs. others)	1.46 (1.05, 2.01)	1.43 (0.99, 2.09)	1.16 (0.65, 2.05)	0.94 (0.48, 1.84)	1.49 (0.98, 2.26)	1.86 (1.11, 3.10)
Technology literacy						
Intellectual tasks (JST-IC), score	1.44 (1.16, 1.78)	1.33 (1.06, 1.68)	1.39 (0.96, 2.02)	1.32 (0.86, 2.02)	1.52 (1.17, 1.97)	1.46 (1.09, 1.94)
Intellectual curiosity (JST-IC), score	1.58 (1.25, 2.00)	1.47 (1.14, 1.90)	1.46 (1.04, 2.05)	1.37 (0.94, 2.01)	1.68 (1.22, 2.32)	1.46 (1.02, 2.09)
Information gathering (JST-IC), score	1.17 (0.998, 1.37)	1.06 (0.88, 1.29)	1.09 (0.86, 1.38)	0.96 (0.72, 1.29)	1.23 (0.995, 1.52)	1.18 (0.90, 1.54)
Creativity (JST-IC), score	1.10 (0.99, 1.23)	1.13 (0.99, 1.28)	1.19 (1.01, 1.40)	1.25 (1.00, 1.55)	1.05 (0.90, 1.23)	1.07 (0.89, 1.28)
Opportunity to socialize (≥1 week)	1.02 (0.74, 1.41)	0.85 (0.59, 1.22)	1.25 (0.75, 2.07)	0.95 (0.50, 1.77)	0.80 (0.52, 1.23)	0.69 (0.42, 1.12)
Health variables						
Physical activity, score	1.04 (0.70, 1.55)	0.94 (0.61, 1.46)	1.32 (0.71, 2.46)	1.25 (0.62, 2.52)	0.81 (0.48, 1.37)	0.65 (0.36, 1.16)
Good dietary variety (vs. bad)	1.15 (0.83, 1.58)	1.33 (0.83, 2.14)	1.02 (0.59, 1.77)	1.49 (0.67, 3.32)	1.09 (0.72, 1.66)	1.21 (0.65, 2.25)
Sleep quality, no (vs. yes)	0.85 (0.60, 1.20)	0.77 (0.54, 1.11)	1.11 (0.66, 1.87)	0.84 (0.47, 1.51)	0.71 (0.45, 1.12)	0.71 (0.43, 1.16)
Obesity (vs. non-obesity)	1.25 (0.88, 1.80)	1.31 (0.89, 1.92)	1.76 (1.06, 2.95)	2.04 (1.15, 3.60)	1.04 (0.61, 1.79)	0.98 (0.54, 1.77)
High blood pressure, yes (vs. no)	0.73 (0.53, 1.01)	0.91 (0.57, 1.46)	0.74 (0.45, 1.23)	1.02 (0.45, 2.32)	0.77 (0.51, 1.17)	0.96 (0.53, 1.74)
Diabetes, yes (vs. no)	1.64 (1.07, 2.51)	1.88 (1.20, 2.96)	1.59 (0.80, 3.17)	2.62 (1.19, 5.77)	1.64 (0.94, 2.85)	1.66 (0.92, 2.97)
Dyslipidemia, yes (vs. no)	1.13 (0.78, 1.64)	1.16 (0.78, 1.72)	1.72 (0.98, 3.02)	2.31 (1.22, 4.39)	0.83 (0.51, 1.36)	0.72 (0.42, 1.23)
Subjective health (vs. unhealthy)	1.08 (0.79, 1.49)	0.94 (0.66, 1.33)	1.36 (0.82, 2.25)	1.15 (0.65, 2.04)	0.95 (0.62, 1.44)	0.83 (0.52, 1.34)
Mild cognitive declines, yes (vs. no)	0.88(0.63, 1.22)	1.21 (0.79, 1.85)	0.70 (0.42, 1.18)	0.97 (0.50, 1.89)	1.09 (0.71, 1.69)	1.52 (0.86, 2.69)
Depression, no (vs. yes)	1.06 (0.75, 1.49)	1.16 (0.81, 1.67)	1.23 (0.72, 2.11)	1.32 (0.73, 2.41)	0.93 (0.59, 1.45)	1.09 (0.67, 1.76)
5-m walking speed test, <1.0 m/s (vs. ≥1.0 m/s)	2.78 (1.09, 7.10)	1.57 (0.90, 2.75)	1.78 (0.52, 6.12)	1.77 (0.72, 4.41)	4.27 (0.993, 18.3)	1.73 (0.79, 3.76)

OR, odds ratio; CI, confidence interval; JST-IC, Japan Science and Technology Agency Index of Competence.*Region.

generalizability of the findings. For this reason, it is desirable to conduct surveys on a national scale and in non-urban areas. Second, the participants comprised older people who spontaneously participated in a health screening. This group is likely to be more health-conscious and, as a result, may predominantly comprise healthier older adults. This implies the need for further validation in populations with different characteristics. Third, since this was a cross-sectional study, we could not determine the temporal changes in the interest in wearable devices. Therefore, we would like to conduct a longitudinal study. Fourth, older adults' acceptance of SW suggests that perceived usefulness, compatibility, and facilitating conditions positively affect to the use of such technologies (15). However, these factors have not been empirically examined. Verification of these factors may mention insights in further acceptance. Finally, purchase intention and usage status were self-reported, which could have led to recall bias.

5 Conclusion

We observed sex differences in factors associated with interest in SW among older adults. Health variables such as obesity, diabetes, and dyslipidemia were associated with interest in SW among men. Moreover, technology literacy, such as the ability to possess new devices and socio-demographics, such as household income and cohabitation status, were associated with interest in SW among women. Age was the only common factor. Therefore, sex-specific strategies are warranted to promote the use of wearable devices for health management among older adults.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Ethics Committee of the Tokyo Metropolitan Institute for Geriatrics and Gerontology approved this study (approval number: R21-056). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

ND: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. YO: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. NK: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. KM: Data curation, Investigation, Writing – review & editing. MI: Data curation, Investigation, Writing – review & editing. HI: Data curation, Investigation, Writing – review & editing. FM: Data curation, Investigation, Writing – review & editing. TO: Data curation, Investigation, Writing – review & editing. HH: Data curation, Investigation, Writing – review & editing. SA: Investigation, Writing – review & editing. HS: Funding acquisition, Methodology, Project administration, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Selected elements of the lifestyle of Silesian seniors, taking into account their participation in the activities of the Third Age Universities

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Introduction: UTA can provide older adult people with the satisfaction of needs and creates the opportunity to pursue youthful interests and passions. The aim of the study was to assess selected elements of the lifestyle of Silesian seniors, taking into account their participation in the activities of Universities of the Third Age.

Methods: The study involved 631 (100%) senior residents of the Silesian agglomeration. The majority of the study group were women (475; 75.28%), and the average age of the participants was 70.28 ± 6.09 years. To conduct the study, an original survey questionnaire was used, complemented by PPS-10, PAQE and Yesavage Geriatric Depression Rating Scale.

Results: Among the surveyed Silesian seniors who did not attend classes at the University of the Third Age, a statistically significantly higher score on the Yesavage's Geriatric Depression Rating Scale was found compared to those confirming their participation in the mentioned activity ($p = 0.002$). Almost 40% (107; 38.63%) of seniors who did not attend classes at the Universities of the Third Age showed a high level of stress, and every fourth (89; 25.14%) Silesian senior taking part in the above-mentioned activity had a low level of stress ($p = 0.04$). The median of points obtained on the physical activity assessment scale (PAQE) by seniors attending classes at Universities of the Third Age was statistically higher than seniors who denied participation in the mentioned activity ($p = 0.017$).

Conclusion: Participation in the various activities at the Universities of the Third Age influenced positively well-being, reduced stress and raised physical activity of examined seniors. It is important to promote and start actions leading to seniors' better and easier inclusion to the society life. Future research should concentrate on reasons why many seniors do not attend activities in their leisure time - especially on accessibility of various activities and financial reasons, which in the future will play crucial role in the aging societies.

KEYWORDS

seniors, Universities of Third Age, physical activity, stress, depression

Introduction

Physical activity is one of the elements of a healthy lifestyle. According to the recommendations of the World Health Organization (WHO), healthy adults should undertake: moderate exercise (at the level of 3–6 MET for 150–300 min/week) or intense exercise (6 or more MET for 75–150 min/week) or an equivalent combination of moderate and intense exercise (1). The latest recommendations of the Institute of Food and Nutrition are also presented in the form of the "Pyramid of Healthy Eating and Physical Activity" at its base (2).

In Poland, the level of physical activity in society is very low, even disturbing. Moreover, with age, the number of people exercising regularly decreases. The study conducted by the Ministry of Sport and Tourism entitled "Level of physical activity of Poles 2018" shows that only 21.8% of Poles met WHO standards regarding the level of physical activity in free time (3).

Regular and systematic physical activity affects, among others: increasing the efficiency of the circulatory system, lowering blood pressure, increasing the stroke volume of the heart and improving the elasticity of blood vessels and reducing the risk of developing atherosclerosis and its complications. In addition, it reduces the risk of stroke, improves metabolism and, consequently, the treatment of obesity and overweight, reduces stress, improves cognitive functions and improves logical thinking processes, concentration of attention and memory. It also contributes to improving well-being (4–7). Researches proves, that regular physical activity promotes better quality and even extension of life (5, 7). The basic task of physical activity in older people is to maintain the appropriate level of psychophysical fitness and physical capacity for as long as possible.

In Poland, the first University of the Third Age (UTA) was established in 1975 in Warsaw as part of the Postgraduate Center for Medical Personnel Education, and was founded by prof. Halina Szwarc. Its aim was to enable older people who could not receive education in their youth to acquire knowledge, implement a continuing education program, conduct gerontological research and improve the quality of life of the older generation. Nowadays, UTA can provide older people with the satisfaction of needs such as: self-education, learning about the environment, being in a group, acceptance, expanding knowledge and skills, filling free time, mental and physical stimulation, learning new technologies and ways of communicating. Moreover, UTA creates the opportunity to pursue youthful interests and passions. Attending classes organized within the UTA allows seniors to undertake various forms of physical activity, shape a healthy lifestyle, but also raise awareness of the importance of exercise in everyday life (8). The aim of the study was to assess selected elements of the lifestyle of Silesian seniors, taking into account their participation in the activities of Universities of the Third Age.

Materials and methods

The research began after obtaining the consent of the Bioethics Committee of the Medical University of Silesia in Katowice - resolution no. PCN/0022/KB1/36/21. The study involved 631 (100%) senior residents of the Silesian agglomeration. The majority of the study group were women (475; 75.28%), and the average age of the participants was 70.28 ± 6.09 years. All methods used in this study were in accordance with applicable guidelines and regulations for conducting scientific research (9).

Inclusion criteria for the study included: age (≥60 years), voluntary, informed consent to participate in the study, ability to follow instructions, ability to read, and no need for assistance from third parties/others in completing the questionnaire. All of the inclusion criteria listed were intended to eliminate any interference from third parties in the process of completing the survey.

For the purposes of statistical analyses, seniors were divided according to: participation in activities at Universities of the Third Age (Yes/No), gender (women/men), age (from 60 to 70 years, from 71 to 80 years), ≥ 81 years of age and education (primary, vocational, secondary, higher) and place of residence (urban/rural).

To conduct the study, an original survey questionnaire was used, containing questions regarding the issues included in the purpose of the work and basic questions including age, gender, place of residence, marital status and level of education.

The Polish version of the PPS-10 questionnaire was used to assess the severity of stress. The questions include an assessment of the intensity of stress related to one's own life situation during the last month (10). Respondents rated the frequency of their feelings and thoughts about life events and situations using a five-point scale, where 0 means "never" and 4 means "very often." The results of the PSS-10 test are expressed in points that reflect the level of stress experienced. Overall, the result can be interpreted as follows: 0–13 points: low stress. Indicates good control over stressors and the ability to cope with them, 14–26 points: average stress level. It may indicate a need to better manage stressors or seek ways to cope with stress, and 27–40 points: high stress level. It indicates a significant burden of stress and the need to take action to reduce it. The Polish version of the questionnaire used in the study was PSS-10 validated by Z. Juczyński and N. Ogińska-Bulik (11).

In order to assess the well-being of the subjects, the Yesavage Geriatric Depression Rating Scale was used. The mentioned scale consists of 15 statements to which each respondent was asked to respond by selecting "yes" or "no." Appropriate calculations and summing up the points allow for the diagnosis of severe or moderate depression or its absence (12).

To assess the physical activity of seniors, the Polish version of the standardized PAQE questionnaire (The Physical Activity Questionnaire for the Elderly) prepared by Król-Zielińska M. et al. was used. This questionnaire provides quantitative data on usual physical activity (including home, sports and recreational activities) over the past year. The PAQE questionnaire is also known as the "modified Baecke questionnaire." In described questionnaire, respondents were asked about their habitual physical activity during the last year, taking into account household, sport and other activities especially in leisure time. For household activity questions there are five possible answers ranging from very active (4 points) to inactive (0 points). The household score, calculated form 10 items, is the sum of all obtained points divided by 10. With regard to sports and other activities, information about the activity type, hours per week, and period of the year in which the activity is normally performed was obtained.

The intensity codes (based on energetic costs of activities) were used to characterize the type of activities. Additionally, codes are provided for hours of the week and periods of the year. The sport and other leisure activity scores (points) are the result of the multiplication of the three codes mentioned above. The total result (points) is the sum of all activity domains (13).

Completing the survey and individual questionnaires was completely anonymous and voluntary. The methods used to collect the questionnaires (placing them in white unmarked envelopes after completing them, collecting the envelopes in one secured place, opening envelopes with completed questionnaires only when entering the obtained results into the database) made it impossible to identify the people participating in the study.

Statistica 13.3 (StatSoft Poland) was used to perform statistical analyses. Because the data obtained showed a non-normal distribution the study used non-parametric tests, including the Mann–Whitney U test and Kruskall-Wallis ANOVA. The Chi^2 test was used for qualitative data. In all analyzes performed, the level of statistical significance was set at $p < 0.05$.

Results

General characteristics of the study group are presented in the Table 1.

The majority of the study group were women (475; 75.28%) and people aged 60 to 70 years (373; 59.11%). Most respondents had secondary education (292; 46.28%), and over 55% (354; 56.10%) of the surveyed group attended classes at Universities of the Third Age.

Table 2 presents the characteristics of the study group, including descriptive statistics and a results of differences analysis in the number of seniors with individual degrees of depression distinguished using the Yesavage's Geriatric Depression Rating Scale Almost 40% (141; 39.83%) of seniors taking part in activities at the University of the Third Age did not show signs of depression, while severe depression was observed in 11 (3.97%) who denied participating in the above-mentioned activity. The observed differences in the number of seniors with particular degrees of depression severity between the compared groups turned out to be statistically significant ($p = 0.004$). This means that attending

TABLE 1 General characteristics of the study group.

Studied group of seniors (n = 631; 100%)						
Variables					n	%
Sex				Women	475	75.28
				Men	156	24.72
Age [years]				60–70	373	59.11
				71–80	220	34.87
M	SD	Min.	Max.	≥81	39	6.18
70.28	6.09	60	96			
Level of education				Primary	37	5.86
				Vocational	120	19.02
				Secondary	292	46.28
				Higher	182	28.55
Place of residence				City	436	69.10
				Rural areas	195	31.90
Attending classes at the University of the Third Age				Yes	354	56.10
				No	277	43.90

n, number; M, average; SD, standard deviation; Min., minimum value; Max., maximum value.

TABLE 2 Characteristics of the studied group of seniors, including the analysis of differences in the number of seniors with individual degrees of depression distinguished using the Yesavage's Depression Assessment Questionnaire.

Seniors' studied group (n = 631; 100%)							
Variables	UTA „+" (n = 354)		UTA „-" (n = 277)		Chi^2		
	n	%	n	%	χ^2	df	p
n i % of the whole group	354	56.10	277	43.90	11.27	2	0.004
n i % of a given group	354	100	277	100			
No depression	141	39.83	78	28.16			
Moderate depression	207	58.47	188	67.87			
Severe depression	6	1.69	11	3.97			

UTA "+", seniors participating in classes at Universities of the Third Age; UTA "-", seniors not participating in classes at Universities of the Third Age; n, number of participants; χ^2, value of the Chi^2 statistic; df, degrees of freedom, p, level of statistical significance.

classes at Universities of the Third Age was associated with a lower risk of developing depression.

Figure 1 shows the characteristics of the study group, taking into account the results of the analysis of differences in the total number of points obtained in the Yesavage's depression assessment questionnaire by seniors attending classes at Universities of the Third Age and those denying participation in the mentioned classes. Supplementary Table S1 presents the characteristics of the studied group, taking into account the descriptive statistics of the points results obtained by seniors attending and not attending classes at Universities of the Third Age in the above-mentioned questionnaire, and Supplementary Table S2 presents the characteristics of the study group of seniors, taking into account the descriptive statistics of the points obtained in the Yesavage's Geriatric Depression Rating Scale questionnaire and attending classes at Universities of the Third Age, sex, age, level of education and place of residence.

Among the surveyed Silesian seniors who did not attend classes at the University of the Third Age, a statistically significantly higher score on the Yesavage's Geriatric Depression Rating Scale was found compared to those confirming their participation in the mentioned activity ($p = 0.002$). Based on the results of the above analysis, it can be assumed that participation in activities at Universities of the Third Age has a positive impact on well-being and reduces the risk of developing depression by maintaining social contacts.

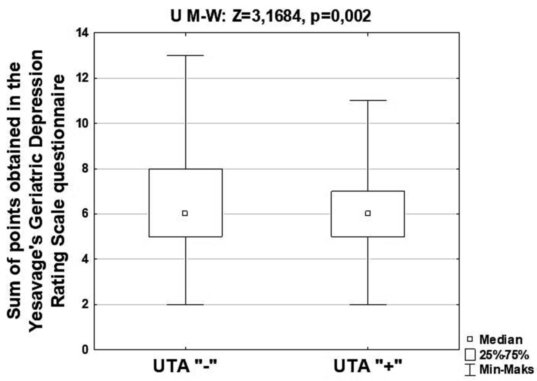

FIGURE 1
Characteristics of the studied group of Silesian seniors, taking into account the results of the analysis of differences in the total number of points obtained in the Yesavage's Geriatric Depression Rating Scale.

The Kruskal-Wallis test showed statistically significant differences ($p < 0.001$) in the number of points scored between seniors aged 60 to 70 who attended ($p < 0.01$), aged 60 to 70 who did not attend ($p = 0.008$) and seniors aged 71 to 80 years old attending ($p = 0.020$) classes at universities of the third age compared to seniors aged 71 to 80 years old who denied participation in the activity in question, who obtained higher point values on the Yesavage's geriatric depression rating scale than the others abovementioned seniors.

The analysis also showed a statistically significant difference ($H = 29.545$; $p = 0.0001$) between the number of points obtained in the Yesavage's Geriatric Depression Rating Scale questionnaire between seniors with primary education ($p = 0.01$) and vocational education ($p = 0.02$) not participating in the activities of Universities of the Third Age, and seniors with higher education participating in the mentioned activity. Seniors with primary and vocational education obtained higher scores on the scale in question compared to respondents with higher education, which may indicate the protective influence of education on the possibility of developing depression among seniors.

The Kruskall-Wallis test also showed statistically significant ($H = 23.655$; $p = 0.0006$) differences in the number of points obtained by seniors living in the cities and taking part in the activities of the Universities of the Third Age, compared to those living in the countryside and denying participation in the discussed activity ($p = 0.03$). Therefore, it can be concluded that living in cities with good access to the discussed activities for seniors has an antidepressant effect. The results of the multiple comparisons described above are presented in the supplementary material (Supplementary Figures S1–S3; tables of multiple comparisons Supplementary Tables S3–S5).

Table 3 presents the characteristics of the study group, taking into account the analysis of differences in the number of respondents with individual degrees of stress intensity distinguished using the PSS-10 stress severity assessment questionnaire, and Figure 2 - taking into account the results of the analysis of differences in the total number of points obtained in the PSS-10 questionnaire by Silesian seniors attending classes at Universities of the Third Age and denying the above-mentioned activity. Supplementary Tables S6, S7 present descriptive statistics of the studied group of Silesian seniors, taking into account the scores obtained in the PSS-10 stress assessment questionnaire and participation in classes at Universities of the Third Age, sex, age, level of education and place of residence.

TABLE 3 Characteristics of the study group, including the analysis of differences in the number of seniors with individual degrees of stress intensity distinguished using the PSS-10 stress severity assessment questionnaire.

Seniors' studied group (*n* = 631; 100%)							
Variables	UTA „+" (*n* = 354)		UTA „-" (*n* = 277)		Chi²		
	n	%	*n*	%	χ^2	df	*p*
n i % of the whole group	354	56.10	277	43.90	5.94	2	0.04
n i % of a given group	354	100	277	100			
Low	89	25.14	52	18.77			
Moderate	157	44.35	118	42.60			
High	108	30.51	107	38.63			

UTA "+" - seniors participating in classes at Universities of the Third Age; UTA "-", seniors not participating in classes at Universities of the Third Age; n, number of participants; χ^2, value of the Chi² statistic; df, degrees of freedom; *p*, level of statistical significance.

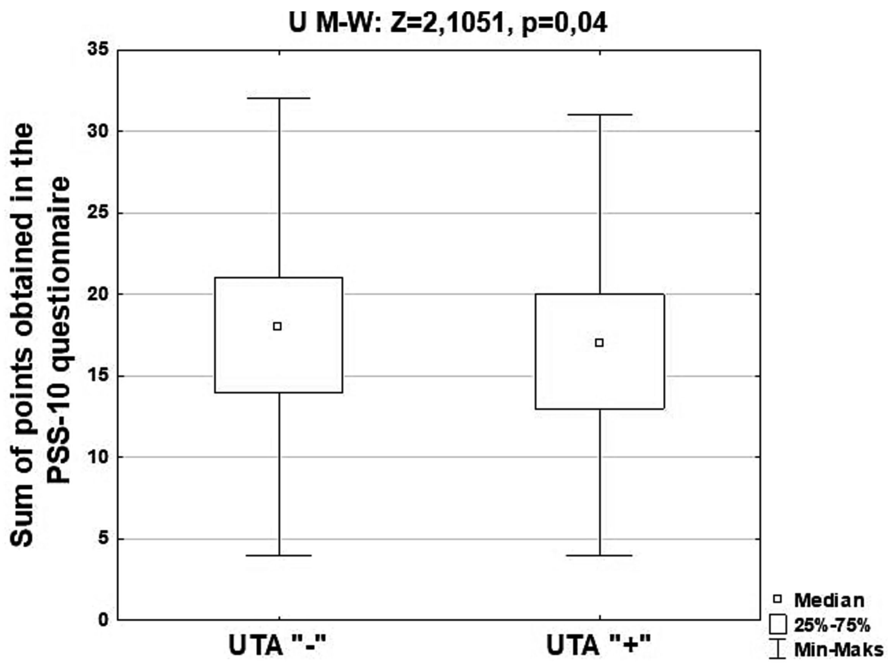

FIGURE 2
Characteristics of the studied group of Silesian seniors, taking into account the results of the analysis of differences in the total number of points obtained in the PSS-10 questionnaire by seniors participating in classes at Universities of the Third Age and denying the above-mentioned activity.

Almost 40% (107; 38.63%) of seniors who did not attend classes at the Universities of the Third Age showed a high level of stress, and every fourth (89; 25.14%) Silesian senior taking part in the above-mentioned activity had a low level of stress. The differences observed between the compared groups in the numbers of individual levels of stress intensity turned out to be statistically significant ($p = 0.04$). Therefore, it can be concluded that participation in the discussed activity will contribute to reducing the level of stress felt.

Comparison tests for many independent groups performed using the Kruskall-Wallis ANOVA test did not show statistically significant differences in the number of points obtained by seniors in the PSS-10 questionnaire depending on attendance at Universities of the Third Age, sex, level of education, participants ‘age and place of residence.

Figure 3 shows the characteristics of the study group, taking into account the results of the analysis of differences in the total number of points obtained in the physical activity assessment questionnaire for seniors (PAQE) by those attending classes at the Universities of the Third Age and those denying described activity, and in Supplementary Table S8 - taking into account attendance or not for classes within Universities of the Third Age, sex, age of participants, level of education and place of residence.

The median of points obtained on the physical activity assessment scale (PAQE) by seniors attending classes at Universities of the Third Age was statistically significantly higher than seniors who denied participation in the mentioned activity ($p = 0.017$). Therefore, it can be concluded that seniors taking part in University of the Third Age activities were in better physical condition than those who did not participate in the above-mentioned activity.

The Kruskal-Wallis test also showed statistically significant ($H = 11.09$; $p = 0.011$) differences in the number of points obtained in the PAQE questionnaire by women participating in classes at Universities of the Third Age, compared to men not participating ($p = 0.015$) in the activity in question. The observed decrease in the median of points obtained could be related to the respondents' attitude toward engaging in physical activity, depending on attending classes at Universities of the Third Age. The results of the described analysis are presented in Supplementary Figure S4, and the results of multiple comparisons are presented in Supplementary Table S9.

The Kruskal-Wallis test showed statistically significant differences in the number of points obtained in the PAQE physical activity questionnaire ($p < 0.001$). Seniors aged 60 to 70 who attended classes at Universities of the Third Age obtained statistically significantly higher results compared to seniors aged 71 to 80 attending ($p = 0.013$) and not attending ($p < 0.001$) and seniors aged ≥81 years ($p = 0.001$) not attending for classes at Universities of the Third Age. The observed decrease in the median number of points obtained was most likely related to the general deterioration of the health and physical fitness of the surveyed seniors as their age increased. The results of the described analysis are presented in Supplementary Figure S5, and the results of multiple comparisons are presented in Supplementary Table S10.

The analysis also showed a statistically significant ($H = 38.848$; $p < 0.001$) difference between the number of points obtained in the PAQE questionnaire among seniors with secondary education attending ($p = 0.029$) and non-participating ($p = 0.007$) and higher education attending classes at Universities of the Third Age, compared to seniors with primary education who did not participate in the discussed activity. The observed increase in the median number of points along with the increase in the level of education and additional participation in activities at Universities of the Third Age could be related to the frequent provision of information about a proper lifestyle during the activity in question. The results of this analysis are

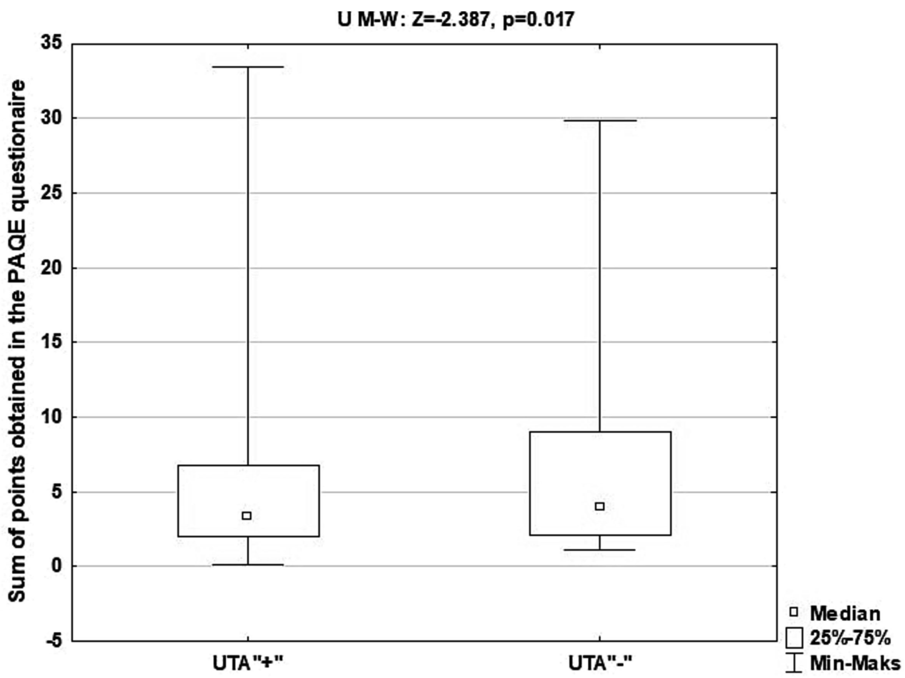

FIGURE 3
Characteristics of the study group, taking into account the results of the analysis of differences in the total number of points obtained in the PAQE questionnaire by seniors attending classes at the University of the Third Age and denying the above-mentioned activity.

presented in Supplementary Figure S6, and the results of multiple comparisons are presented in Supplementary Table S11.

The Kruskal-Wallis test comparing the number of points obtained in the PAQE physical activity questionnaire between the respondents did not show statistically significant ($H = 7.720$; $p = 0.05$) differences in the number of points obtained by seniors living in cities participating and not participating in the activities of the Universities of the Third Age. The observed lack of a statistically significant difference may be related to the small group of participants, and its enlargement may contribute to obtaining a statistically significant result and further conclusions in the compared groups. The results of the mentioned analysis are presented in Supplementary Figure S7, and the results of multiple comparisons are presented in Supplementary Table S12.

Figure 4 shows the characteristics of the study group, including the analysis of differences in the number of points obtained in the PAQE questionnaire and the level of stress in seniors.

The Kruskal-Wallis test did not show statistically significant difference ($H = 3.945$; $p = 0.14$) in the number of points obtained by seniors in the PAQE physical activity questionnaire depending on the severity of depression measured using the Geriatric Depression Rating Scale questionnaire. Moreover, the mentioned test showed statistically significant differences between the intensity of stress examined using the PSS-10 questionnaire and the points obtained by the respondents when assessing physical activity with the PAQE questionnaire ($H = 15.389$; $p = <0.001$). Post-hoc analysis showed statistically significant differences in the number of points obtained by seniors with low versus moderate ($p = 0.03$) and low versus high ($p < 0.001$) levels of stress intensity. The observed differences can be explained by the fact that the increased physical activity of the surveyed seniors reduced stress.

Discussion

In our study, almost 40% (141; 39.83%) of seniors participating in activities at Universities of the Third Age did not show signs of depression, while severe depression was observed in 11 (3.97%) seniors who denied participating in the mentioned activity, and the mentioned differences were statistically significant ($p = 0.004$). Older adult depression is a popular and difficult to diagnose condition. It is often confused with dementia (14). However, research shows that seniors cared for by the environment around them are less likely to experience symptoms of depression than those left to themselves (15). Attending classes at Universities of the Third Age allows seniors to develop social contacts with peers and awakens their sense of "being needed," which has a positive impact on their well-being and quality of life (8). This was also confirmed by our own research, where a statistically significantly higher score on the Geriatric Depression Rating Scale according to Yesavage, compared to respondents confirming their participation in the above-mentioned activity ($p = 0.002$), which proves that participation in University of the Third Age activities had a positive impact on well-being and reduced the risk of developing depression by maintaining social contacts. In their research, I. Wróblewska and J. Błaszczyk showed that the most common motive for taking up activities at Universities of the Third Age by seniors was the desire to expand their knowledge and maintain intellectual fitness (93; 81.58%), and for more than half (63; 55 0.26%) – maintaining bonds with people from the same age group (16).

In her work on the contemporary needs of Universities of the Third Age, M. Sulik quoted a student of the University of Third Age in Katowice who stated that "*loneliness is a paralyzing factor and it is highly advisable to seek new acquaintances or contacts with nice people*

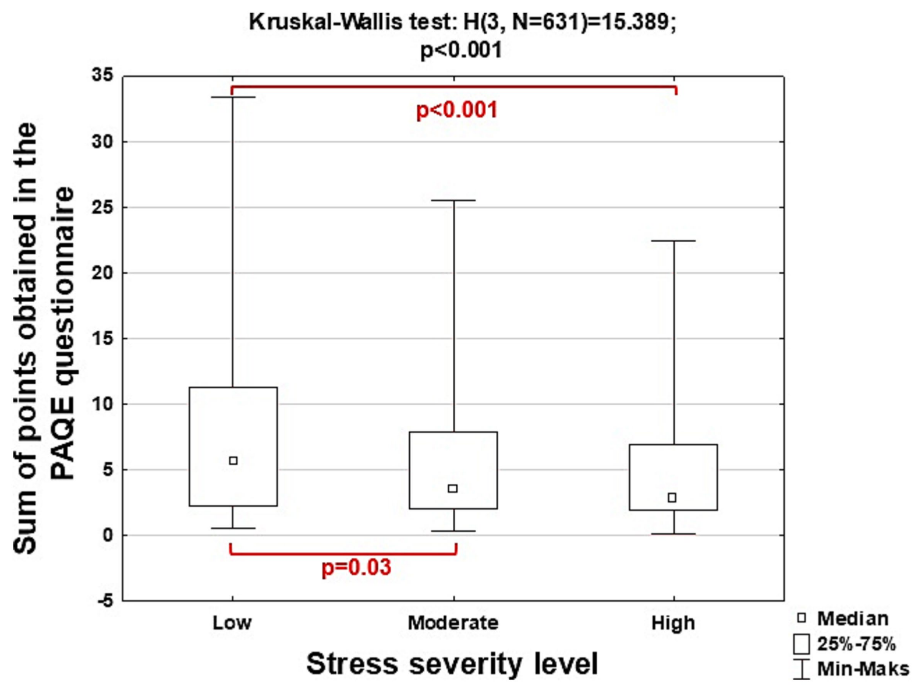

FIGURE 4
Characteristics of seniors taking into account the results of the analysis of differences in the total number of points obtained in the PAQE questionnaire depending on the level of stress intensity.

with similar interests. Such opportunities were offered by the UTA, and belonging to this group of students triggered new interests in me, stimulated my activity, and allowed me to discover interesting places in the immediate vicinity and throughout our country" (17). Based on observations in our study, it can also be concluded that participation in classes at Universities of the Third Age had a positive impact on reducing the level of depression, especially among "younger" seniors (over 60 years of age), educated and those living in cities where access to the offer of classes conducted by Universities of the Third Age is much larger (18).

Our study involving a group of Silesian seniors attending classes at the University of the Third Age showed a statistically significantly lower score on the PSS-10 stress scale compared to the results of the surveyed seniors who denied participation in the mentioned activity ($p = 0.04$). Almost 40% (107; 38.63%) of seniors who did not attend classes at Universities of the Third Age showed a high level of stress, while every fourth (89; 25.14%) senior who took part in the above-mentioned activity declared a low level of stress - the mentioned differences were also statistically significant ($p = 0.04$). Stress is one of the main factors determining overall life satisfaction. J. Czapiński confirmed this in his research, in which he showed that the occurrence of stressful situations negatively affects human mental health (19). Pawlikowska-Łagód K. et al. showed that the general satisfaction of seniors with life deteriorates as the level of stress increases (20). Stress also influences the development of depression (14). Many universities also organize classes on techniques for dealing with stressful situations, and research shows that seniors attending classes at Universities of the Third Age are better able to cope with stress (21).

According to the study "*Gender differences in mental disorders and suicide in Europe*" conducted in 2014 in cooperation with European universities, women were more exposed to stress and coped with it worse than men. According to the cited studies, this is a direct result of more responsibilities imposed on women in connection with professional work and running the house - as if they worked two jobs, thus providing themselves with a large dose of stress (22, 23). Our study involved retired seniors, so no statistically significant differences were found in the number points obtained by seniors in the PSS-10 questionnaire depending on gender, but also level of education, age and place of residence. There are reports in the literature that living in the countryside is associated with a low level of stress (24, 25), and working in positions requiring higher education - with a high level of stress (26, 27). However, the mentioned studies were conducted in groups of people of working age, not among seniors.

B. Lejzerowicz-Zajązkowska and P. Hajduk conducted an analysis of the aging society, in which they showed that physical activity had a significant impact on increasing independence and self-reliance, and thus improved the quality of life of older people (28). In our study, the median of points obtained on the physical activity assessment scale (PAQE) by the surveyed seniors participating in the activities of the Universities of the Third Age was statistically significantly higher than the respondents who denied participation in the discussed activity ($p = 0.017$), meaning that the seniors participating in the activities were more physically active, than the rest. Universities of the Third Age organize many activities related to physical activity for seniors contributing to improvement of quality of their health and life (8).

Seniors attending the above-mentioned classes are also better educated about not only the positive impact of physical activity on the body, but also the principles of leading a healthy lifestyle than seniors who do not participate in them (8). Our study also confirmed a statistically significant ($H = 38.848$; $p < 0.001$) differences between the number of points obtained in the PAQE questionnaire among seniors and their level of education. The observed increase in the median number of points along with the increase in the level of education and participation in activities at Universities of the Third Age could be related to the frequent provision of information about a proper lifestyle during the activity in question.

Our study also compared the number of points obtained in the PAQE physical activity questionnaire and place of residence showed no statistically significant differences in the number of points obtained by seniors living in cities participating and not participating in the activities of the Universities of the Third Age. This showed that seniors living in cities and taking part in UTA activities are not more physically active than those who do not take part in the above-mentioned activity.

Our study showed that women attending University of the Third Age classes were significantly more likely to engage in physical activity compared to men who did not participate in the above-mentioned classes. K. Witkowski et al. examined the physical activity of women over 55 years of age, and their research showed that 111 (93%) of the respondents systematically practiced some form of physical activity, and the most popular of them were walking (38; 31%) and Nordic walking (31; 26%) (29). Women also seem to be more motivated to participate in the activities of Universities of the Third Age, as evidenced by statistics: according to the report of the Department of Social Research and Living Conditions of the Statistical Office in Gdańsk (Poland), women constituted as much as 86.00% of all students of Universities of the Third Age (30). Therefore, they are more likely to take part in activating activities and translate positive habits related to regular physical activity into everyday life.

A statistically significant reduction was observed in the number of seniors aged ≥81 years ($H = 35.93$; $p < 0.001$) engaging in physical activity and not attending University of the Third Age classes compared to "younger" seniors participating in the above-mentioned activity ($p = 0.001$). According to the previously cited report of the Department of Social Research and Living Conditions of the Statistical Office in Gdańsk, the largest age group, comprising 59.7% of all UTA students, were people aged 60 to 70, and people over 76 years of age only 11% (30). The reduction in the number of "older" participants in classes offered by Universities of the Third Age, as well as the reduction in their level of physical activity, was most likely related to the general deterioration of the health and physical fitness of the surveyed seniors with age.

In their research on the importance of physical activity in the prevention of depressive disorders, T. Saran et al. came to the conclusion that in the absence of health contraindications, regular physical exercise can be a form of prevention of depressive disorders, as well as a technique complementing pharmacological treatment and psychotherapy of depressive disorders (31). J. Tackas also mentioned the important role of physical activity in the prevention and treatment of depressive disorders (32). K. Melnik et al. confirmed that physical activity may affect mental health, and potentially also the risk of developing various mental disorders, and may even serve as a method of treating them (33).

Statistically significant differences were found between the intensity of stress examined using the PSS-10 questionnaire and the points obtained by seniors in the assessment of physical activity using the PAQE questionnaire ($H = 15.389$; $p < 0.001$). There were also statistically significant differences in the number of points obtained by respondents with low versus moderate ($p = 0.03$) and low versus high ($p < 0.001$) levels of stress intensity, which could be explained by the fact that the increased physical activity of the surveyed seniors resulted in a reduction of stress. Many researchers have previously obtained similar results showing the beneficial effect of physical activity on reducing stress levels. Examples include the research of K. Zając et al., in which a significant reduction in the level of perceived stress was noted as a result of regular participation in organized group general gymnastics classes in a group of women over 60 years of age (34), or M. Lipko-Kowalska, who, researching physical activity of women of mature age, in her work she presented, among others, the most common reasons for undertaking the above-mentioned activity by the respondents, and these were: the desire to maintain health, not only physical, but also mental (35). Studies conducted in other groups of respondents also confirmed the discussed results (36–38). According to many reports already cited in the initial report, physical activity allows, among other things, to reduce stress and contributes to improved well-being (4–7). At this stage, the limitations of the study include a relatively small group of seniors participating in University of the Third Age activities. Moreover, there were definitely more women, seniors aged 61–70, as well as seniors living in urban areas, where there is a greater opportunity to choose UTA classes, however the last factor may have a misleading impact on seniors' attendance at UTA classes. Additionally, all surveyed seniors lived in the same area of the Silesian agglomeration. Nevertheless, this study showed the relationship between leading a healthy lifestyle, as well as the reduction or complete absence of symptoms of depression and stress in the group of seniors with their participation in the discussed activities of the Universities of the Third Age, and also gave an insight into the possibility of preventing the mentioned symptoms thanks to the integration of older people and satisfying their social and intellectual needs. To conclude all obtained and discussed result it can be stated that better well-being and stress reduction of the surveyed seniors, as well as their greater physical activity, were associated with participation in activities at the Universities of the Third Age. Our study proves that activities undertaken by seniors have a real impact on their life and wellbeing. Our study also proves that it is important to promote and start actions leading to seniors' better inclusion to the society life especially those influencing their health-promoting habits and helping to maintain their focus and memory functions. This study is a prove for municipal authorities that implementation of discussed actions can slow down the health deterioration and help to preserve good aging of different regions inhabitants. Moreover, it could have positive impact not only for seniors but also people meeting with them who can take from their knowledge and experience. Future research should concentrate on reasons why many seniors do not attend activities in their leisure time - especially on accessibility of various activities and financial reasons, which in the future will play crucial role in the aging societies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The research began after obtaining the consent of the Bioethics Committee of the Medical University of Silesia in Katowice - resolution no. PCN/0022/KB1/36/21. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JD: Conceptualization, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MS: Data curation, Formal analysis, Methodology, Resources, Validation, Writing – original draft, Investigation, Writing – review & editing. EŁ: Data curation, Methodology, Writing – original draft. OS: Formal analysis, Resources, Writing – original draft, Validation, Writing – review & editing.

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Social isolation, regardless of living alone, is associated with mortality: the Otassha study

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Introduction: Social isolation has been recognized as a contributing factor to negative health outcomes. Although living alone is associated with health-related outcomes, existing findings are inconsistent. It is not the act of living alone that may predict poor health, but rather social isolation that can lead to increased mortality risk. This study investigated the combined associations of social isolation and living alone with mortality among community-dwelling older adults.

Methods: We included older adults from Itabashi ward, Tokyo, who participated in comprehensive health checkups. Participants were categorized into four groups based on their social isolation status and living alone. The primary outcome was all-cause mortality, analyzed using Cox proportional hazards models.

Results: Of the 1,106 participants (mean age 73, 42% male), 4.5% experienced both social isolation and living alone. This combination was associated with a worse prognosis regarding all-cause mortality (hazard ratio (HR): 2.08 [95% confidence interval (CI), 1.08–4. 00]). Those who were socially isolated but not living alone also showed a trend towards higher mortality risk (HR: 1.41 [95% CI, 0.90–2.20]). Contrastingly, those who were not socially isolated and lived alone did not show an increased mortality risk (HR: 0.81 [95% CI, 0.44–1.49]).

Discussion and conclusion: Living alone is not inherently associated with a poor prognosis in older adults; however, social isolation was associated with a higher mortality risk. Healthcare providers should focus on enhancing social interactions and support for older adults because of their effects on health rather than solely addressing living arrangements to prevent adverse health events.

KEYWORDS

social isolation, living alone, interactions with others, prognosis, older adults

1 Introduction

Social isolation is characterized by a lack of contact with family, friends, or others (1) and is estimated to affect approximately 25% of older adults (2). The prevalence of social isolation has risen, partly because of the COVID-19 pandemic in 2020, which significantly cut down on in-person interactions (3). This condition is associated with adverse health outcomes, including dementia, cardiovascular disease, and increased mortality (4–6). Therefore, preventing these negative health outcomes in socially isolated older adults is a critical public health concern.

Social isolation is typically defined by objective interactions with others; some past research have incorporated living alone into their assessment of social isolation (7, 8). In recent years, there has been an increase in the number of older adults living alone in communities, and some studies have observed an association between living alone and a higher rate of mortality and dementia (9, 10). Consequently, preventing negative outcomes among older adults living alone has become an important concern. However, there is an inconsistent agreement on the association between living alone and health-related outcomes. Sarwari et al. found that older adults living alone often function better than those living with others because they are required to carry out daily activities on their own (11). Similarly, Zhao et al. found no correlation between living alone and a higher mortality risk (12). Our previous research also indicates that poor social networks, rather than living alone, are associated with adverse events (13).

These findings indicate that living alone does not automatically lead to worse health outcomes; the social isolation that often accompanies it may raise the risk of mortality. However, the specific association between mortality and the combination of social isolation and living alone has not been thoroughly investigated. Understanding these relationships is crucial for preventing adverse health effects in older adults who live alone. In recent years, the frequency of interaction with others, used as an indicator of social isolation, has been segregated between face-to-face and non-face-to-face interactions, and its association with mortality has been reported (7). The importance of non-face-to-face interactions is recognized, as the COVID-19 pandemic has considerably limited face-to-face interactions (14, 15). It is thus essential to differentiate between these types of social isolation and assess how they influence health outcomes when combined with living alone.

This study aimed to examine how the combination of living alone and social isolation affects mortality rates among community-dwelling older adults. Furthermore, we also aimed to assess social isolation considering both face-to-face and non-face-to-face interactions and examine the relationship between the combination of living alone and mortality.

2 Materials and methods

2.1 Participants

Data were collected from the Otassha Study, an ongoing longitudinal study focused on comprehensive health checkups among community-dwelling older adults. The Otassha Study began in October 2011 and involves annual health checkups to date. At the beginning of the study, we sent a mail recruitment letter to all residents aged 65–84 years who were registered in the Basic Resident Register, excluding institutionalized residents and participants from previous surveys conducted by our institute. We followed up with our participants annually, and new participants were recruited on an annual basis as they turned 65 years of age. These checkups within the cohort were discussed in prior studies (16, 17). For this study, we included participants who participated in either the 2012 or 2013 surveys and who completed evaluations regarding living alone and social isolation. The study adhered to the ethical guidelines of the Declaration of Helsinki. All participants provided written informed consent, and the Tokyo Metropolitan Institute for Geriatrics and Gerontology approved the research protocol (2012-H35).

2.2 Social isolation and living alone

Social isolation was defined by the frequency of interactions with others. The study questionnaire has been used to measure social isolation in a number of studies and has been reported to be associated with outcomes like disability and mortality (18, 19). The study participants reported how often they interacted with family not living with them, relatives, friends, and neighbors, both in person and through other means such as by phone, e-mail, or letters. Their answers were classified as follows: (1) 6 or 7 times a week (almost every day), (2) 4 or 5 times a week, (3) 2 or 3 times a week, (4) about once a week, (5) 2 or 3 times a month, (6) about once a month, (7) less than once a month, (8) no contact, or (9) none. Drawing from prior studies, we defined "social isolation as a low frequency of face-to-face interaction" for those with in-person contact less than once a week (18, 19). A similar definition was applied for "social isolation as a low frequency of non-face-to-face interaction." Social isolation was ultimately defined as having both types of interactions less than once a week.

To ascertain their living status, the participants were asked about their living arrangements. Those who responded with "living alone (not living with others)," were categorized as living alone, while those who answered, "living together," were placed in the not living alone group.

2.3 Other variables

During the checkups, we assessed age, sex, body mass index (BMI) (<18.5, 18.5–24.9, or $\geq 25\,kg/m^2$), self-rated health (SRH), instrumental activities of daily living (IADL), number of comorbidities, alcohol consumption, smoking status (current, former, or never), depressive symptoms, subjective economic status, education years, usual gait speed, and cognitive function. SRH was assessed using a four-point Likert scale: (1) excellent, (2) good, (3) fair, and (4) poor, with responses later categorized as either good (excellent/good) or poor (fair/poor) (20). IADL was evaluated with a subscale from the Tokyo Metropolitan Institute of Gerontology Index of Competence (21), where scores range from 0–5, with 5 indicating full independence. Chronic diseases such as hypertension, stroke, heart disease, diabetes, hyperlipidemia, anemia, kidney disease, chronic obstructive pulmonary disease, and cancer were identified through nurse interviews. According to the number of chronic diseases, the participants were classified into three categories (0, 1, and 2+). Depressive symptoms were assessed using the Zung Self-Rating Depression Scale comprising 20 questions, and a score of 50 or higher was defined as having depressive symptoms (22). Subjective economic status was determined based on the question, "Generally speaking, are you financially comfortable?" This was determined based on the question, "In general, are you financially comfortable?" The participants were asked to answer using one of the following responses: (1) have much financial leeway, (2) have financial leeway, (3) average, (4) financially tight, or (5) financially very tight. If the respondents answered (4) financially tight, or (5) financially very tight, they were classified as having a poor economic status. Usual gait speed was tested over a 5 m course, with an additional 3 m before and after acceleration and deceleration, timed manually with a stopwatch. This speed was recorded once and calculated by dividing the distance by the time (m/s). Individuals with a normal gait speed of <1.0 m/s were classified as having a slow gait speed. Cognitive function was measured using the Mini-Mental State Examination (MMSE), which scores from 0 to 30, with higher scores reflecting better cognitive function. Participants with scores ≤23 were considered to have cognitive impairment (23). The trained examiners administered both gait speed and cognitive function tests.

2.4 All-cause mortality

All-cause mortality data were sourced from a database managed by the ward office. This mortality information was provided through the notification of death forms for residents. The follow-up period began on the date of initial participation in the 2012 survey (September 25–October 5, 2012) or the 2013 survey (October 7–18, 2013), which served as the baseline. The follow-up was extended up to November 1, 2020, marking the maximum follow-up duration.

2.5 Statistical analysis

To investigate the combined association of social isolation and living alone, participants were categorized into four groups based on these criteria: Group 1, no social isolation and not living alone; Group 2, no social isolation, living alone; Group 3, social isolation, not living alone; and Group 4, social isolation and living alone. We examined the baseline differences between the four groups using χ^2 tests for categorical data and analysis of variance (ANOVA) for continuous data.

We visualized the cumulative survival curves for all-cause mortality across the four groups using the Kaplan–Meier method. Furthermore, we applied the log-rank test to assess survival differences among the groups. The association between the groups and all-cause mortality was examined using Cox proportional hazards regression. This analysis included a univariable model and two multivariable models. Model 1 adjusted for age, sex, BMI, self-rated health, number of comorbidities, and IADL, while model 2 further adjusted for depressive symptoms, subjective economic status, education years, slow gait speed, and cognitive impairment, in addition to the covariates in the first model. We also explored the relationship between social isolation in face-to-face and non-face-to-face interactions, living alone, and mortality using the same Cox proportional hazards model. In sensitivity analyses of the possible influence of reverse causation, we performed sensitivity analyses using the same statistical approach, after excluding individuals who died during the first 1 year of follow-up. Furthermore, to examine whether the association between the combination of social isolation and living alone and mortality differed by age and sex, we performed subgroup analyses by stratifying the sample into two age groups (65–74 and 75+) and by sex.

Descriptive results are shown using the data, including missing values. For missing data on confounders, we performed multiple imputations using the chained equations method, assuming that the analyzed data were missing at random (24). Results from 20 imputed data sets were combined for analysis using Rubin's formula. The following variables were incorporated into the imputation model: social isolation, living arrangement, covariates, and outcome variables.

3 Results

3.1 Participant characteristics

Out of the total 1,122 participants surveyed in 2012–2013, 16 were excluded because of missing data on social isolation or living arrangements, leaving 1,106 participants for the final analysis. Table 1 presents the participant characteristics, stratified by combined social isolation and living alone. Of the total sample, 532 participants (48.1%) experienced a low frequency of face-to-face interaction, while 394 (35.6%) had a low frequency of non-face-to-face interaction. A total of 243 participants (22.0%) were experiencing social isolation, and 260 (23.5%) were living alone. Additionally, 50 participants (4.5%) were identified as group 4, experiencing both social isolation and living alone. The χ^2 tests and ANOVA revealed that individuals in group 4 were typically older, male, with poorer self-rated health, less likely to have never consumed alcohol or smoked, had more depressive symptoms and poor subjective financial status, shorter education years, had slower gait speeds, and had lower MMSE scores. Group 3 was the only group in which fewer than 90% of participants were independent in terms of IADLs.

3.2 Association between combined social isolation and living alone and all-cause mortality

During the median follow-up period of 96 months (interquartile range: 84–97 months), a total of 118 deaths occurred. Figure 1 presents the Kaplan–Meier survival analysis results for the four groups categorized by social isolation and living alone. The log-rank test indicated that groups 3 and 4 experienced significantly lower survival rates ($p < 0.001$).

Table 2 shows the association between the combination of social isolation and living alone and all-cause mortality. In model 2, group 4 had a significantly higher risk of mortality (hazard ratio (HR): 2.08 [95% confidence interval (CI), 1.08–4.00]). Group 3 did not show a statistically significant association with increased mortality risk (HR: 1.41 [95% CI, 0.90–2.20]), but had a higher incidence rate (IR) than groups 1 and 2 (group 1, IR: 12.2, group 2, IR: 8.7, group 3, IR: 22.3). The combination of social isolation based on low frequency of face-to-face interactions and living alone did not show a statistically significant association in any group; however, the group of social isolation (group 3, IR: 16.1, group 4, IR: 22.7) had higher IR than the no social isolation group (group 1, IR: 12.8, group 2, IR: 7.2). The combination of social isolation based on low frequency of non-face-to-face interactions and living alone showed a significantly higher risk of mortality in the social isolation group regardless of living alone status (group 3, HR: 1.63 [95% CI, 1.07–2.48], group 4, HR: 1.98 [95% CI, 1.04–3.77]).

TABLE 1 Characteristics of participants stratified by the combinations of social isolation and living alone.

	Missing	Total	No SI × Not LA	No SI × LA	SI × Not LA	SI × LA	*p*-value
		N = 1,106	*N* = 653	*N* = 210	*N* = 193	*N* = 50	
Age (years)	0	73.0 (5.6)	72.7 (5.5)	73.1 (5.8)	73.6 (5.7)	74.2 (6.2)	0.07
Male (%)	0	41.5	42.9	18.1	57.0	62.0	<0.01
BMI (kg/m^2)	8	23.0 (3.4)	23.1 (3.5)	22.9 (3.4)	22.5 (2.8)	22.7 (3.4)	0.16
<18.5		7.5	7.3	7.2	7.3	12.0	0.24
18.5–24.9		67.8	66.2	67.5	74.9	62.0	
≥ 25.0		24.8	26.5	25.4	17.8	26.0	
Self-rated health, poor (%)	36	18.3	15.2	19.8	22.2	36.7	<0.01
Number of chronic diseases (%)	3						0.68
0		31.2	30.5	33.8	33.2	22.0	
1		33.7	33.5	34.8	32.1	38.0	
2+		35.1	36.0	31.4	34.7	40.0	
IADL, full mark (%)	23	91.9	92.7	96.6	83.2	93.8	<0.01
Alcohol consumption status (%)	1						<0.01
Current		52.3	54.2	43.1	57.0	48.0	
Former		8.5	5.4	10.0	14.0	22.0	
Never		39.2	40.4	46.9	29.0	30.0	
Smoking status (%)	1						<0.01
Current		11.8	10.1	10.5	15.0	26.0	
Former		26.0	25.4	15.8	35.8	38.0	
Never		62.3	64.5	73.7	49.2	36.0	
Zung Depression Scale	12	34.6	33.5	35.8	35.3	40.7	<0.01
Depressive symptoms (%)		6.5	4.5	8.7	7.5	20.0	<0.01
Poor subjective financial status (%)	9	21.9	19.9	20.1	26.2	38.0	<0.01
Education years (years)	9	12.4 (2.7)	12.7 (2.7)	12.2 (2.7)	12.4 (2.7)	11.0 (2.5)	<0.01
Usual gait speed (m/s)	20	1.3 (0.3)	1.4 (0.2)	1.3 (0.3)	1.3 (0.3)	1.2 (0.3)	<0.01
<1.0 m/s		8.4	6.4	9.2	12.1	16.7	0.01
MMSE score	26	28.1 (2.3)	28.2 (2.2)	28.2 (2.1)	27.6 (2.6)	27.7 (1.9)	0.02
≤ 23 points		4.5	4.2	3.9	6.4	4.2	0.61

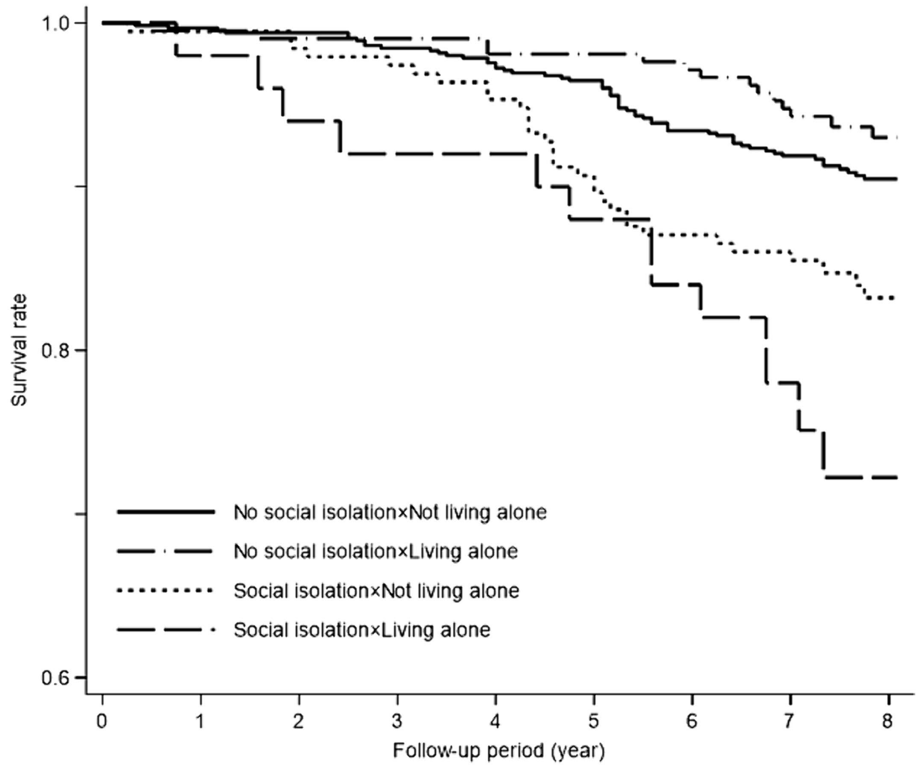
Data are presented as mean (SD) for continuous measures, and *n* (%) for categorical measures.
BMI, body mass index; IADL, instrumental activity of daily living; MMSE, mini-mental state examination; SI, social isolation; LA, living alone.

In the analyses that excluded mortality that occurred during the first 1 year, although the associations of combined social isolation and living alone with outcomes were weakened, the results were not substantially different from those of the primary analyses (Supplementary Table S1). In the subgroup analyses by sex and age group, the association between combined social isolation and living alone and mortality was attenuated in some analyses in groups 3 and 4, but as in the primary analysis, the group of social isolation had a higher IR regardless of living alone. *p*-values for tests of interaction were not significant (Supplementary Tables S2, S3).

4 Discussion

These results showed that the co-existence of social isolation and living alone was associated with a worse prognosis. Specifically, a significant reduction in non-face-to-face interactions was associated with a poorer prognosis, independent of living alone. These results suggest that living alone does not necessarily increase the risk of mortality, but social isolation, characterized by a decrease in interactions, is associated with an increased mortality risk.

In this study, group 4 (social isolation and living alone) was independently associated with worse prognosis, even after adjusting for subject characteristics, psychological and social factors, cognitive function, and gait speed. Group 3 (social isolation and not living alone) also had a higher IR of mortality, although this was not statistically significant. That is, social isolation was associated with higher risk of mortality, regardless of whether the participants lived alone. Although previous studies have found an association between social isolation or living alone and prognosis separately (6, 9), this is the first study to report the combined effect of social isolation and living alone on prognosis. Several



Number at risk

	0	1	2	3	4	5	6	7	8
No social isolation×Not living alone	653	651	649	643	637	630	610	600	444
No social isolation×Living alone	210	209	208	208	206	206	204	199	145
Social isolation×Not living alone	193	192	190	188	184	175	168	166	109
Social isolation×Living alone	50	49	47	46	46	44	42	39	25

FIGURE 1
Results of Kaplan–Meier analyses for the incidence of death.

mechanisms have been reported to be associated with social isolation and mortality (25). These include physiological factors, such as activation of the hypothalamic–pituitary–adrenal axis and increased chronic stress response; psychological factors, such as more likely to be depressed or suicidal; and behavioral factors, like more likely to smoke, drink alcohol, and make poor dietary choices and no exercise habit (25). In the present data, the socially isolated groups (groups 3 and 4) were characterized by a higher percentage of people with poor self-rated health and depressive symptoms, and a higher percentage of people with a history of drinking and smoking. Thus, these factors may have triggered physiological factors such as activation of the hypothalamic–pituitary–adrenal axis and increased chronic stress response, which may have been associated with poor prognosis. However, since this study was could not investigate physiological factors, these mechanisms need to be further verified.

Conversely, group 2 (not socially isolated x living alone) showed no association with mortality. A previous study also reported that older adults living alone was not associated with mortality (12), which is consistent with the present findings. Older adults living alone, especially women, may be physically healthier than older adults living with others (11), and furthermore, older adults who interact with others, as in group 2, may receive more encouragement from those around them to maintain a healthy lifestyle (26, 27). These findings underscore the importance of assessing social isolation, rather than living arrangements, when determining the risk of adverse events in older adults.

We categorized the frequency of interaction as face-to-face or non-face-to-face and examined its association with reduced interaction, living alone, and all-cause mortality. Results showed that regardless of whether a participant lived alone or not, reduced non-face-to-face interactions, such as phone calls and e-mails, were associated with worse prognosis. Recent studies have reported that non-face-to-face interactions have protective effects on health outcomes (28, 29). Non-face-to-face interactions make it easier to seek advice, exchange health information, and receive support from distant relatives and friends. These benefits may be important not only for the older adults themselves, but also for distant family and friends to help prevent health problems in the older adults. However, reduced face-to-face interaction was not significantly associated with mortality. Previous studies have found that face-to-face interaction is also effective in preventing disability and maintaining mental health (28, 30). A difference with the results of the present study is the possible confounding of depressive symptoms, gait ability, and cognitive function. In the present study, the association with mortality was not significant after adjustment for variables such as depressive symptoms, slow gait speed, and cognitive decline, so the reduction in face-to-face interactions may be more critical in older adults with depressive symptoms, slow gait speed, or cognitive decline. However, the small number of such subjects in the overall study population may have

TABLE 2 Association between combination of social isolation and living alone and all-cause mortality.

	Number of events	IR*	Crude model		Adjusted model 1		Adjusted model 2	
			HR (95% CI)	*p* value	HR (95% CI)	*p* value	HR (95% CI)	*p* value
Social isolation × living alone								
No social isolation × Not living alone	60	12.2	Reference		Reference		Reference	
No social isolation × Living alone	14	8.7	0.71 (0.40–1.27)	0.25	0.86 (0.47–1.57)	0.62	0.81 (0.44–1.49)	0.50
Social isolation × Not living alone	31	22.3	1.86 (1.20–2.87)	<0.01	1.47 (0.94–2.29)	0.08	1.41 (0.90–2.20)	0.13
Social isolation × Living alone	13	37.6	3.14 (1.72–5.72)	<0.01	2.47 (1.33–4.60)	<0.01	2.08 (1.08–4.00)	0.03
Social isolation (defined as Low frequency of face to face contact) × living alone								
No social isolation × Not living alone	41	12.8	Reference		Reference		Reference	
No social isolation × Living alone	8	7.2	0.56 (0.26–1.19)	0.13	0.66 (0.30–1.42)	0.28	0.62 (0.28–1.35)	0.23
Social isolation × Not living alone	50	16.1	1.26 (0.84–1.91)	0.27	1.06 (0.70–1.61)	0.78	1.04 (0.69–1.59)	0.84
Social isolation × Living alone	19	22.7	1.78 (1.04–3.07)	0.04	1.77 (1.02–3.09)	0.04	1.53 (0.86–2.72)	0.15
Social isolation (defined as Low frequency of non-face to face contact) × living alone								
No social isolation × Not living alone	42	10.6	Reference		Reference		Reference	
No social isolation × Living alone	13	9.1	0.86 (0.46–1.61)	0.64	1.01 (0.53–1.93)	0.98	0.95 (0.50–1.82)	0.89
Social isolation × Not living alone	49	21.1	2.03 (1.34–3.06)	<0.01	1.67 (1.10–2.54)	0.02	1.63 (1.07–2.48)	0.02
Social isolation × Living alone	14	26.7	2.56 (1.40–4.68)	<0.01	2.31 (1.24–4.28)	0.01	1.98 (1.04–3.77)	0.03

IR, incidence rate; CI, confidence interval; HR, hazard ratio; SI, social isolation; LA, living alone; BMI, body mass index; IADL, instrumental activity of daily living; MMSE, mini-mental state examination. Adjusted model 1: age; sex, BMI, self-rated health, number of comorbidities, and IADL. Adjusted model 2: Adjusted model 1+ depressive symptoms, subjective financial status, education years, slow gait speed, and cognitive impairment. Incidence rate* = incidence rate per 1,000 person-years.

masked these effects. Future studies are needed in populations with a wide range of subject characteristics, such as frailty and mild cognitive impairment.

This study has several limitations. First, this study was conducted in Itabashi ward, Tokyo, which is an urban area. Therefore, there may be differences in characteristics between older adults living in this area and those living in rural areas. Moreover, the participants of this study were not randomly selected, which may introduce a selection bias toward older adults with high health awareness. In fact, most of the participants of this study had high IADL ability (>90% independent) and normal gait speed, indicating a high level of functioning and mobility. Previous research has shown a higher risk of adverse health outcomes in older adults with frailty and those living alone with reduced functional capacity (11). Therefore, we should be cautious when applying our findings to frail individuals or older adults living alone with reduced functional capacity, as they may have different patterns and consequences of social isolation and living alone. Second, we measured non-face-to-face interactions through phone calls and e-mails but did not account for the use of social media, which has become increasingly popular among older adults with the rise of communication technology (31). Third, there may also be unmeasured confounders that may affect both social isolation and mortality, such as marital history, reason for living alone, onset and duration of social isolation and living alone. Therefore, we cannot rule out the possibility of residual confounding by other factors that we did not measure or control for. This information would allow a more detailed analysis of the association between the combination of social isolation and living alone and mortality. Finally, in this study, we defined social isolation based on the frequency of interactions with others. This method has been widely used in previous studies targeting community-dwelling older adults. However, there is no standardized method for measuring social isolation, and some studies have evaluated social isolation from the aspects of social support and social activities (32). Therefore, this study may have only assessed one aspect of social isolation. Future studies may need to evaluate social isolation from a broader perspective of social relationships.

In conclusion, this study has shown that social isolation is associated with a poor prognosis, regardless of whether one lives alone. Older adults living alone do not necessarily have a higher risk for health-related outcomes, so the frequency of interactions with others and support from others should also be assessed. Health care providers should focus on assessing the social isolation status of older adults to prevent adverse events.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the datasets presented in this article are not readily available because of ethical and privacy restrictions. Requests to access these datasets should be directed to imamura@tmig.or.jp.

Ethics statement

The studies involving humans were approved by Ethics committee of the Tokyo Metropolitan Institute for Geriatrics and Gerontology. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

KIm: Formal analysis, Methodology, Software, Visualization, Writing – original draft. HK: Data curation, Investigation, Methodology, Project administration, Resources, Validation, Writing –review & editing. ME: Investigation, Writing –review & editing. HS: Investigation, Resources, Writing – review & editing. HH: Investigation, Resources, Writing – review & editing. YF: Investigation, Resources, Writing – review & editing. KIh: Investigation, Resources, Writing – review & editing. SO: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1365943/full#supplementary-material

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Projecting trends in the disease burden of adult edentulism in China between 2020 and 2030: a systematic study based on the global burden of disease

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Purpose: This study was based on the Global Burden of Disease (GBD) database and aimed to analyze the trend of disease burden for complete edentulism in Chinese adults between 1990 and 2030, and to provide valuable information for the development of more effective management and preventive measures.

Methods: Data on Chinese adults with complete edentulism from 1990 to 2019 was analyzed using GHDx data. Descriptive analyses were used to analyze changes in the prevalence and burden of complete edentulism, gender and age distribution between 1990 and 2019. In addition, we used an autoregressive integrated moving average (ARIMA) model to predict the trend of disease burden for Chinese adults with complete edentulism between 2020 and 2030.

Results: The incidence, prevalence, and rate of YLDs in adults with complete edentulism in China showed an increasing trend from 1990 to 2019. In 2019, the incidence was 251.20 per 100,000, the prevalence was 4512.78 per 100,000, and the YLDs were 123.44 per 100,000, marking increases of 20.58, 94.18, and 93.12% from 1990. Males experienced a higher increase than females. However, the standardized rates decreased over the same period. The ARIMA model predicts a subsequent upward and then downward trend for all indicators between 2019 and 2030, except for the standardized incidence rate which remained essentially unchanged. Specifically, the incidence is predicted to decrease from 388.93 to 314.40 per 100,000, prevalence from 4512.78 to 3049.70 per 100,000, and YLDs from 123.44 to 103.44 per 100,000. The standardized prevalence and YLDs rates are also expected to decrease.

Conclusion: The burden of complete edentulism in China is projected to show an increasing trend from 2020 to 2022 and a decreasing trend from 2023 to 2030. Despite the decline in the burden of disease associated with complete edentulism in China, many problems remain to be solved.

KEYWORDS

complete edentulism, GBD, incidence, prevalence, YLDs

1 Introduction

The case definition of complete edentulism includes any individual with zero remaining permanent teeth; toothlessness of infancy is not included. Missing teeth often generate multiple adverse effects; on the one hand, this will lead to reduced chewing ability and limited food choices, especially for the older adult. Patients with missing teeth tend to avoid choosing fruits, vegetables, nuts and other tougher but healthy food that is needed by the body, thus resulting in an imbalance in nutritional intake (1–5). On the other hand, missing teeth will also lead to alveolar bone resorption, shortening of the vertical distance of the lower third of the face, relaxation of the facial muscles, lip and cheek subsidence, and other changes in appearance, thus resulting in an aging face, unclear pronunciation, along with psychological and social disorders (6). Although no direct causal relationship has been detected between total edentulousness and death (7), research has shown that missing teeth can influence systemic diseases and may increase the risk of stroke, myocardial ischemia, coronary heart disease, cognitive impairment and other diseases (8–11).

Missing teeth place a heavy economic burden on society. The economic burden of oral disease is the fourth highest of all diseases in most industrialized countries around the world; in 2010, the global economic burden of oral disease was $442 billion, of which the direct cost of treatment was $298 billion, or approximately 4.6% of global health expenditure (12). Between 2010 and 2015, indirect costs increased by 21.0% as a result of oral diseases, with 67.0% of lost productivity attributable to severe tooth loss (fewer than nine permanent teeth) (13). As the most populous country in the world, research predicts that the proportion of the older adult population (aged 65 years and above) in China will reach 19.25% by 2030 (14), and that this country will enter a stage of heavy aging, where the burden of diseases caused by missing teeth in the older adult will increase and become a social problem that cannot be ignored.

In a previous study, we found that the incidence, prevalence, and years lived with disability (YLDs) of Chinese adults with missing teeth were followed an increasing trend between 1990 and 2019, while the standardized incidence, prevalence, and YLDs showed a decreasing trend (15); this opposing trend was due to the increasing aging of the population. As population aging in China becomes further aggravated, it is important to investigate whether future changes in the trends of the rate and the standardized rate are consistent. Therefore, in this study, we constructed an autoregressive integrated moving average (ARIMA) model to predict the disease burden in China between 2020 and 2030. This can not only provide a scientific basis for the scientific formulation of national public health policies and the rational allocation of medical and health resources, but also provide a reference for health administrations to determine the priority areas of disease prevention and control, and the formulation of strategies for the prevention and control of chronic diseases.

2 Materials and methods

2.1 Data sources

The incidence, prevalence and YLDs associated with missing teeth and their corresponding age-standardized rates (ASRs) in China between 1990 and 2019 were obtained from the Global Health Data Exchange query tool.[1] The disability weighting for missing teeth in the GBD 2019 study was 0.067 (0.045–0.095) and can be used to estimate the Disability-adjusted life years (DALYs) for missing teeth. Age-standardized rates for missing teeth were based on the GBD 2019 global age-standardized population. DALYs are a crucial demographic indicator in the GBD and represent the sum of YLLs and YLDs. Deaths caused directly by oral disease are uncommon. Therefore, only YLDs were used in this study. YLDs are calculated by summing the frequency (prevalence), severity (weight of disability), and duration of a condition. The reliability of GBD data has been confirmed by previous studies (15–22).

2.2 Definition of complete edentulism

The case definition of complete edentulism includes any individual with no remaining permanent teeth, excluding edentulousness in infancy. This disease is evaluated by quantifying its incidence and estimating the primary sequelae; specifically, asymptomatic and symptomatic complete edentulism resulting in significant difficulty in eating meat, fruits, and vegetables. A small body of evidence suggests that complete edentulism predisposes individuals to an increased risk of ischemic cardiovascular events, including myocardial infarction and stroke. These sparse data have been incorporated into models that estimate the excess mortality in individuals with complete tooth loss. However, as this association is considered ecological rather than causal, tooth loss was not estimated as an underlying cause of death. Therefore, this was included in the analysis of risk factors for cardiovascular disease. The International Classification of Diseases (ICD) codes for tooth loss mapped to the Global Burden of Disease list of causes are K08.0–K08.499 for ICD10; and 525.0–525.19, 525.4–525.54 for ICD9 (19).

2.3 Statistical analyses

An ARIMA model is a type of differential, integral, moving average and autoregressive model, also known as an "integral moving average autoregressive model", and represents a model that is commonly used to use time series of data for forecasting analysis. In the ARIMA model (*p, d, q*), AR is "autoregressive", *p* is the number of autoregressive terms, MA is "moving average", *q* is the number of terms in the moving average, and d is the number of differences (orders) that provide a smooth series (23). The optimal model was automatically filtered by Akaike information criterion (AIC) and Bayesian information criterion (BIC). In this study, the ARIMA model was used to analyze the burden of disease based on the trend for disease burden and to predict the burden of disease associated with complete edentulism in China between 2020 and 2030. All analyses and data visualization were implemented using R3.6.0 software. The accuracy of the model was determined by mean absolute error (MAE), root mean square error (RMSE), mean square error (MSE), mean absolute percentage error (MAPE), symmetric mean absolute

1 http://ghdx.healthdata.org/gbd-results-tool

percentage error (SMAPE) and other indicators for validation; a smaller MAPE value indicated a smaller error.

3 Results

3.1 Distribution of incidence, prevalence, and YLDs rate of missing teeth by sex and age in China (2019)

The age and sex distribution of the burden of disease for complete edentulism in 2019 is shown in Table 1. The incidence, prevalence and YLD rates for complete edentulism were lowest in the 15–49-year group; there was a rapid upwards trend after the age of 50 years, and the highest rates were evident in the oldest age group (70 years and above; an incidence of 1,908.06/100,000, a prevalence of 28,311.20/100,000, and a YLD rate of 751.03/100,000). Comparison of the disease burdens for complete edentulism between different genders revealed that the incidence, prevalence and YLD rates were higher in females than in males.

3.2 Forecasts for the incidence, prevalence, and YLDs rates of complete edentulism in China (2020–2030)

Predictions of the incidence, prevalence, and YLDs of complete edentulism, and the incidence, prevalence, and YLDs of standardized complete edentulism, in Chinese adults with missing teeth from 2020 to 2030 are shown in Table 2 and Figure 1. Between 2020 and 2030, the incidence and standardized rates of complete edentulism in Chinese adults with missing teeth show a tendency to first increase and then decrease. Projections showed that between 2019 and 2030, the prevalence of missing teeth in China will decrease from 388.93/100,000 to 314.40/100,000, a reduction of 19.16% when compared with 2019. The standardized prevalence of missing teeth in China is projected to increase slightly from 272.15/100,000 to 277.48/100,000, an increase of 1.79% when compared with 2019. The prevalence of missing teeth in China is projected to decrease from 4512.78/100,000 to 3049.70/100,000, a reduction of 32.42% when compared with 2019. The standardized prevalence of missing teeth in China is projected to decrease from 3327.48/100,000 to 2043.77/100,000, a reduction of 38.58% when compared with 2019. The YLDs of missing teeth in China is projected to decrease from 123.44/100,000 to 103.44/100,000, a reduction of 16.20% compared with 2019. Finally, the standardized YLDs of missing teeth in China is projected to decrease from 90.52/100,000 to 84.32/100,000, a reduction of 6.85% when compared to 2019.

4 Discussion

Alongside economic development, there have been significant changes in the lifestyle of the population and a marked improvement in the standard of living over recent years; however, this has inevitably been accompanied by changes in the spectrum of human diseases. Over recent years, chronic and non-communicable diseases have become a key topic of global concern and increasing research attention has been paid to complete edentulism in different countries and regions. There has been a significant increase in research efforts in the basic, clinical, and public health fields related to complete edentulism, a phenomenon that reflects the significant health and economic burdens imposed on human society by chronic diseases. As the most populous country, the prevention and treatment of complete edentulism in China has become a significant problem. Investigating the epidemiological distribution of complete edentulism and analyzing the trends of disease burden associated with complete edentulism over the next 10 years in large datasets generated domestically and internationally is very important if we are to develop methods to prevent and treat complete edentulism. Such studies can provide supportive data and the theoretical basis for the government to formulate prevention and control policies for complete edentulism.

In this study, we found that the disease burden associated with complete edentulism increased with age and that most of this burden was concentrated in individuals aged 70 years and over. The burden of disease was lowest in individuals aged 15–49 years, thus suggesting that changes in the age composition of the population exert changes in the trend of the disease burden for complete edentulism. The proportion of individuals in China aged 65 years and older increased from 26.32 million to 200 million between 1953 and 2021; this represents 4.4 to 14.2% of the population. This may be one of the main reasons for the overall increase in the disease burden associated with complete edentulism in China. This is because the risk of caries, periodontal disease, diabetes mellitus and other diseases associated with tooth loss increases with age, thus increasing the prevalence and incidence of tooth loss. The trends in age change observed in the present study were similar to those reported by the Fourth National Oral Health Survey in China in 2015 (24), thus suggesting the validity and reliability of the study, which used GBD data. Although there are some differences in the disease burden of complete edentulism in terms of gender, previous studies have shown that because complete edentulism is associated with many factors, more studies are needed to confirm this despite the fact that the disease burden of complete

TABLE 1 The age and sex distribution of the burden of disease for edentulism in China, 2019.

Age	Incidence			Prevalence			YLDs		
	Both	Male	Female	Both	Male	Female	Both	Male	Female
All ages	388.93	301.64	479.63	4512.78	3205.16	5871.56	123.44	88.52	159.72
15–49 years	78.59	57.59	100.71	884.38	586.43	1198.07	25.53	17.02	34.49
50–69 years	787.63	612.69	962.66	7386.47	5559.47	9214.56	206.26	156.32	256.23
70+ years	1908.06	1712.15	2072.33	28311.20	21947.90	33646.73	751.03	589.57	886.41

YLDs, years lived with disability.

TABLE 2 Projections of edentulism in China between 2020 and 2030 (1/100,000).

Year	Incidence (95% CI)		Prevalence (95% CI)		YLDs (95% CI)	
	Rate	Standardization rate	Rate	Standardization rate	Rate	Standardization rate
2020	470.91 (456.98–484.83)	308.88 (247.70–370.07)	5474.05 (5321.16–5626.93)	3928.77 (3119.64–4737.9)	148.69 (118.26–178.12)	109.68 (106.23–113.13)
2021	513.06 (464.61–561.51)	312.40 (279.86–344.93)	6078.01 (5528.01–6628.01)	4203.61 (3850.48–4556.75)	159.67 (119.04–205.30)	123.10 (113.20–133.01)
2022	529.04 (439.65–618.43)	306.12 (256.75–355.49)	6512.47 (5478.58–7546.35)	4248.30 (3646.17–4850.42)	165.38 (136.80–193.96)	128.88 (112.34–145.41)
2023	524.70 (398.71–650.69)	300.64 (241.57–359.7)	6483.10 (4978.20–7988.00)	4071.75 (3293.74–4849.77)	167.59 (128.01–207.18)	126.47 (104.31–148.63)
2024	505.61 (409.00–512.21)	295.85 (230.34–361.35)	6055.82 (5092.66–7018.98)	3720.08 (2838.83–4601.34)	164.43 (125.43–203.43)	116.74 (90.68–142.8)
2025	476.85 (396.23–557.47)	291.67 (221.65–361.69)	5537.59 (4594.45–6780.73)	3265.64 (2343.73–4187.56)	157.25 (110.21–204.29)	101.74 (73.67–129.81)
2026	442.84 (344.56–541.13)	288.01 (214.73–361.29)	4880.12 (3870.43–5889.82)	2792.92 (1866.39–3719.44)	147.91 (94.52–201.29)	104.27 (75.65–132.89)
2027	407.20 (296.82–517.58)	284.82 (209.15–360.49)	4191.83 (3102.8–5380.86)	2383.27 (1452.51–3314.03)	137.10 (79.09–195.12)	107.40 (78.77–136.02)
2028	372.71 (254.71–390.72)	282.04 (204.59–359.48)	3686.36 (2792.45–5580.26)	2101.46 (1139.89–3063.03)	125.54 (74.37–176.71)	93.91 (64.84–122.98)
2029	341.36 (219.03–463.68)	279.60 (200.83–358.37)	3304.62 (2361.09–4248.14)	1985.82 (965.19–3006.45)	114.11 (60.97–167.24)	95.87 (55.39–136.35)
2030	314.40 (189.95–438.84)	277.48 (197.71–357.25)	3049.70 (2883.83–4015.57)	2043.77 (955.55–3131.99)	103.44 (59.25–147.63)	84.32 (51.76–116.88)

YLDs, years lived with disability.

edentulism is known to be higher in females than in males (15); in the present study, we found that this difference was statistically significant.

In the present study, we used an ARIMA model for time series analysis to fit and predict the incidence, prevalence, and rate of YLDs in Chinese adults with rate and standardized rate complete edentulism. The rates and standardized rates of complete edentulism were projected to first increase and then decrease between 2020 and 2030, with an overall downwards trend. The relatively consistent downward trends in the rates and standardized rates suggest that the disease burden associated with complete edentulism in China will still follow a downwards trend by 2030, despite further aging of the population. Between 2019 and 2030, the prevalence rate in China is expected to decline by 32.42%, equivalent to 2.94% per year. This downwards trend is in line with projections for both Germany and the United States. In a previous study, Falk Schwendicke reported an expected decline of more than 65% between 2014 and 2030 (equivalent to 4.1% per year) (25). Another study reported that the United States is expected to experience a 30% reduction in the number of edentulous individuals in 2050 when compared to 2010. Other authors projected a 2.6% reduction in the prevalence of edentulousness by 2050 (26). Furthermore, the magnitude of the decline expected in different countries is closely related to population aging. According to Mayra Cardoso, by 2040, the prevalence of edentulousness in Brazil will be almost zero in adolescents, 1.77% in adults and 85.96% in the older adult (27).

The burden of edentulous disease is projected to rise between 2020 and 2023, possibly due to the fact that during the Coronavirus Disease (COVID-19) pandemic (2019–2023), dental services were not readily available to patients due to policy and personal factors; furthermore, patients did not generally attend hospitals for oral treatment except for emergencies such as traumatic injuries and acute endodontitis (22, 28). As a result, the incidence and prevalence of missing teeth are likely to increase as many teeth that could have been treated and preserved were not attended to in the clinic in a timely manner. In addition, the prevalence of caries and periodontal disease, the main causes of tooth loss, remain at a high level in China.

The disease burden associated with complete edentulism in China is projected to follow a decreasing trend between 2023 and 2030; this reduction is likely to be due to the introduction of a series of policies by the state. The National Health and Wellness Commission released the Healthy Dental Action Programme (2019–2025) on 31 January 2019, with separate age-appropriate programmes for the age-related high incidence of different diseases (caries, periodontal disease, and missing teeth).

In order to reduce the incidence of dental caries among adolescents, a special "sugar reduction" campaign has been proposed; this requires primary and secondary schools, and childcare institutions, to restrict the sale of sugar-sweetened beverages and snacks, and to reduce the supply of sugar-sweetened beverages and sugar-sweetened foods in canteens (19, 23). Furthermore, the campaign promotes the implementation of intervention models for oral disease, such as children's oral health check-ups, the prevention of caries by sealing grooves in the first molar, and the use of topical fluoride, by the health sector in conjunction with the education sector. There is a clear requirement to strengthen oral health and control the rate of caries in 12-year-old children to less than 25% by 2030. For middle-aged and older adult people, the prevention of periodontal disease is the main

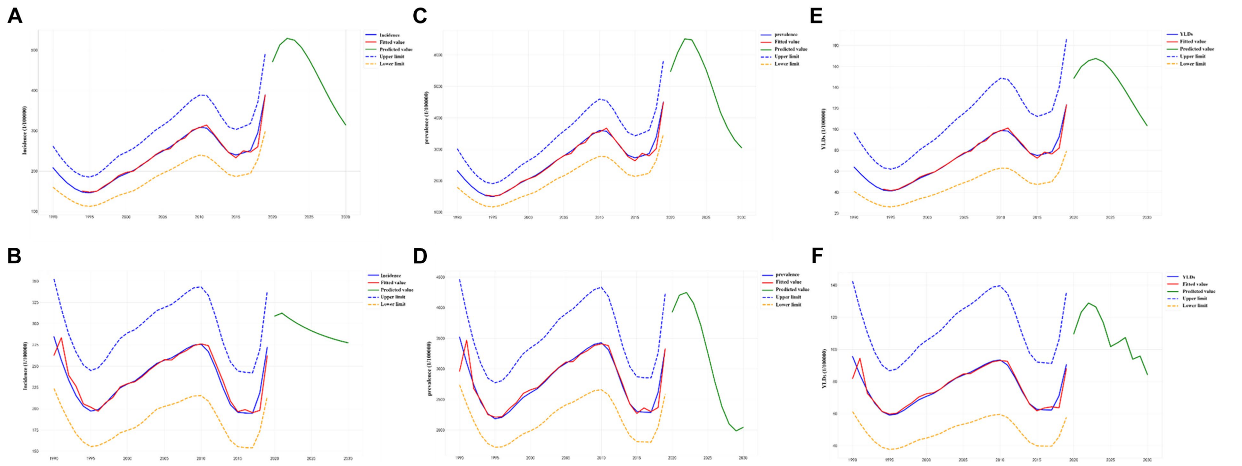

FIGURE 1
Projected disease burden for edentulism in China between 2020 and 2030. **(A)** Incidence. **(B)** Standardized incidence. **(C)** Prevalence. **(D)** Standardized prevalence. **(E)** YLDs. **(F)** Standardized YLDs. YLDs, years lived with disability.

focus, and high-risk behavioral interventions for oral diseases are proposed. The construction of a smoke-free environment has been strengthened, the smoking ban in public places has been comprehensively promoted, and the supervision and enforcement of tobacco control in public places has been strictly enforced. In areas where the chewing of betel quid is a habit, efforts are focused on the oral health hazards of long-term betel quid chewing, targeted publicity and education, and oral health check-ups; this strategy will promote the early diagnosis and treatment of diseases such as periodontal and oral mucosal lesions. It is also important to promote the use of oral health-care products, such as health-care toothbrushes, fluoride-containing toothpaste and dental floss, promote the inclusion of oral health examinations in routine medical check-ups, and advocate the regular acceptance of oral health examinations, preventive oral cleaning, early treatments and other services for the prevention and treatment of oral diseases. It is also important to promote guidance and intervention for the prevention and treatment of oral diseases among the older adult, advocate that the older adult pay attention to the relationship between oral health and systemic health, strengthen the oral health management of patients with hypertension, diabetes and other chronic diseases among the older adult, and actively provide services such as the prevention and treatment of caries, periodontal diseases, oral mucosal diseases, and prosthetic denture repair. It is explicitly required that by 2025, the number of teeth retained by older adult people aged 65–74 years (in pieces) will reach 24.

President Xi Jinping proposed that we should "integrate health into all policies" at the National Conference on Health and Health, which fully embodies our government's policy of integrating oral health concepts into general health (29).

Moreover, forecasts indicate that China's economic, scientific and technological strength, along with comprehensive national power, will attain a new levels between 2020 and 2030, and that the economy will embark on a road of development that is higher quality, more efficient, fairer, more sustainable, and more secure. Furthermore, it is expected that the economic growth rate will enter the "5 era", with an average annual growth rate of approximately 5.3%. In addition, during the period of the Fourteenth Five-Year Plan (2021–2025), the average annual growth rate of China's economy will reach approximately 5.3%; during the period of the Fifteenth Five-Year Plan (2026–2030), the growth rate will reach approximately 5.1% (30). The relationship between socioeconomics and the disease burden of complete edentulism is complex (31). On the one hand, many studies have found that a higher socioeconomic status is a protective factor against complete edentulism (25, 32, 33) and that the economy raises the level of education as well as cognitive ability. These factors are known to influence oral hygiene practices or the ways in which individuals interact with healthcare services, ultimately affecting the incidence and prevalence of complete edentulism. On the other hand, economic improvements at the national level may increase the types and quantities of ultra-processed foods and all types of beverages, thus increasing the prevalence of caries and periodontal disease, thereby also increasing the disease burden of complete edentulism (34). In addition, some cultures, especially females of a higher socioeconomic status, may choose dentures because they are concerned about their appearance and the appearance of their teeth; this may, in part, increase the prevalence of complete edentulism in areas with better economic levels (31).

Although the initial stage of the introduction of the national policy has not been fully implemented, the burden of tooth loss disease in China between 2019 and 2023 is expected to follow an increasing trend. However, with the further implementation of the policy, and as the country's future economic level continues to improve, the burden of tooth loss disease in China after 2023 is likely to follow a decreasing trend.

5 Conclusion

Between 2020 and 2030, the burden of complete edentulism in China is predicted to initially increase between 2020 and 2023 and then decrease from 2023 onwards, thus showing an overall decreasing trend. Previous studies have shown that complete edentulism significantly affects the quality-of-life, self-esteem, and nutritional status of patients (35). Our analyses provide reassuring evidence of a general and equitable improvement in the oral health status of the Chinese population. However, further efforts are needed to address potential risk factors for tooth loss in the older adult population, promote tooth retention into advanced age, and manage tooth loss in an appropriate manner. The interpretation of the results in this study focused on the adult level rather than the individual level, thus indicating a need for more individual-based studies to enhance our findings in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

XQ: Writing – original draft. LC: Writing – review & editing. XY: Writing – review & editing. DL: Writing – review & editing. QL: Writing – review & editing. XZ: Writing – review & editing. FM: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1367138/full#supplementary-material

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Decoding emotional resilience in aging: unveiling the interplay between daily functioning and emotional health

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Background: EPs pose significant challenges to individual health and quality of life, attracting attention in public health as a risk factor for diminished quality of life and healthy life expectancy in middle-aged and older adult populations. Therefore, in the context of global aging, meticulous exploration of the factors behind emotional issues becomes paramount. Whether ADL can serve as a potential marker for EPs remains unclear. This study aims to provide new evidence for ADL as an early predictor of EPs through statistical analysis and validation using machine learning algorithms.

Methods: Data from the 2018 China Health and Retirement Longitudinal Study (CHARLS) national baseline survey, comprising 9,766 samples aged 45 and above, were utilized. ADL was assessed using the BI, while the presence of EPs was evaluated based on the record of "Diagnosed with Emotional Problems by a Doctor" in CHARLS data. Statistical analyses including independent samples *t*-test, chi-square test, Pearson correlation analysis, and multiple linear regression were conducted using SPSS 25.0. Machine learning algorithms, including Support Vector Machine (SVM), Decision Tree (DT), and Logistic Regression (LR), were implemented using Python 3.10.2.

Results: Population demographic analysis revealed a significantly lower average BI score of 65.044 in the "Diagnosed with Emotional Problems by a Doctor" group compared to 85.128 in the "Not diagnosed with Emotional Problems by a Doctor" group. Pearson correlation analysis indicated a significant negative correlation between ADL and EPs ($r = -0.165$, $p < 0.001$). Iterative analysis using stratified multiple linear regression across three different models demonstrated the persistent statistical significance of the negative correlation between ADL and EPs (B = –0.002, $\beta = -0.186$, $t = -16.476$, 95% CI = –0.002, –0.001, $p = 0.000$), confirming its stability. Machine learning algorithms validated our findings from statistical analysis, confirming the predictive accuracy of ADL for EPs. The area under the curve (AUC) for the three models were SVM-AUC = 0.700, DT-AUC = 0.742, and LR-AUC = 0.711. In experiments using other covariates and other covariates + BI, the overall prediction level of machine learning algorithms improved after adding BI, emphasizing the positive effect of ADL on EPs prediction.

Conclusion: This study, employing various statistical methods, identified a negative correlation between ADL and EPs, with machine learning algorithms confirming this finding. Impaired ADL increases susceptibility to EPs.

KEYWORDS

activities of daily living (ADL), emotional problems (EPs), machine learning algorithm, the China health and retirement longitudinal survey (CHARLS), Barthel index (BI), support vector machine (SVM), decision tree (DT), logistic regression (LR)

1 Introduction

As the world's population continues to age, projections indicate that the number of individuals aged 60 and above in developing nations will surge from 900 million to two billion between 2015 and 2050 (1). Among the older adult population, the activities of daily living (ADL) and emotional problems (EPs) have received widespread attention in the fields of medicine and public health research (2–6). EPs encompass a range of disorders such as panic disorder, generalized anxiety disorder, social phobia, specific phobia, obsessive-compulsive disorder, post-traumatic stress disorder, and depression (7). These EPs pose significant challenges to individual health and quality of life (8). Research has found that the overall prevalence of depression among older adults globally is 28.4% (9), and depression may accelerate the cellular aging process (10). Symptoms of depression, anxiety, and other emotional issues also manifest in the preclinical stages of Alzheimer's disease (AD) (11). EPs greatly impact the health and lifespan of the older adult. Therefore, in the context of global aging, it is particularly important to meticulously explore the factors behind emotional issues.

EPs, characterized primarily by emotional disturbances such as depression, anxiety, mania, and feelings of loneliness, may also entail impulsive behavior, disruptions in sleep and diet, and even suicidal or self-harming thoughts (12). For middle-aged and older adult individuals, the pressures of work and family, or difficulties adjusting to life after retirement, coupled with disparities in social interaction and attention, can lead to emotional disruptions, resulting in a spectrum of EPs (13). In the prodromal stages of AD, which often coincide with gradual and insidious impairments in ADL, individuals may experience EPs, manifesting as depression or anxiety, yet these symptoms often go unnoticed, leading to exacerbation in later stages of AD (14, 15). During the recovery and sequelae phases of stroke, EPs are often present (16), with patients frequently experiencing difficulty in emotional regulation, thereby impacting stroke rehabilitation (17, 18). ADL encompasses a range of pertinent issues such as personal self-care, proficiency in functional tasks, and the ability to perform activities, serving as a cornerstone of an individual's quality of life (19). Age-related impairments in ADL may render middle-aged and older adult individuals unable to accept declines in physical function and personal capabilities, thereby triggering EPs (20). Encouraging patients to improve their ADL is a crucial measure in the rehabilitation of EPs, as enhancing ADL can aid patients in returning to normal life and stabilizing their emotions (21). In stroke rehabilitation, as patients' physical abilities improve, activities such as independent eating, walking, and climbing stairs can alleviate EPs resulting from stroke sequelae (22, 23).

Previous studies have hinted at the potential correlation between ADL and EPs. To elucidate this correlation further, the present study collected data from the China Health and Retirement Longitudinal Survey (CHARLS) in 2018 and employed various statistical methods for analysis, revealing a significant correlation between ADL and EPs. Additionally, three machine learning algorithms—Support Vector Machine (SVM), Decision Tree (DT), and Logistic Regression (LR)—were employed to validate our findings. The primary objective of this study is to elucidate the association between ADL and EPs, enhance the awareness of ADL among middle-aged and older adult individuals, and introduce novel avenues for non-pharmacological rehabilitation therapy for emotional issues in this demographic group.

2 Methods

2.1 Study population

This study collected data from the China Health and Retirement Longitudinal Study (CHARLS) baseline dataset, which is operated by the National School of Development at Peking University.[1] CHARLS has established a high-quality open-access database encompassing various details regarding individuals, families, health status, and socio-economic aspects, including "Health Status and Functioning," "Cognition," "Work Retirement," and "Family Information." The study cohort comprised individuals aged 45 and above randomly selected from 150 counties or districts and 450 villages or urban areas across 28 provinces, representing the middle-aged and older adult population in China (24). Utilizing the 2018 CHARLS dataset, this study encompassed a total of 20,813 samples. Participants under 45 years old were excluded from the analysis, along with those with insufficient demographic or health data, resulting in a final sample size of 9,766 individuals.

2.2 Assessment of emotional problems

The assessment was conducted based on the records of emotional problems data "Diagnosed with Emotional Problems by a Doctor" in CHARLS. The samples were divided into two cohorts: those affirmed as "Diagnosed with Emotional Problems by a Doctor" and those negated as "Not diagnosed with Emotional Problems by a Doctor."

1 http://charls.pku.edu.cn

2.3 Assessment of ADL

The Barthel Index (BI) is a recognized method used to assess the level of ADL. In this study, the BI was employed to evaluate the ADL of all samples. The BI categorizes daily activities into 10 independent elements, including "Feeding," "Bathing," "Grooming," "Dressing," "Bowel Control," "Bladder Control," "Toilet Use," "Transfers," "Mobility," and "Stairs," each element being assessed with a score (Table 1), reflecting the individual's ability and proficiency in completing the respective tasks. By assigning scores to each element and summarizing these scores, the BI is derived, ranging from 0 to 100. A higher BI score indicates greater autonomy and proficiency in performing daily life activities (6, 25–27).

2.4 Assessment of covariates

The covariates in this study were derived from the CHARLS dataset, encompassing variables such as age, gender (male, female), residence (Central of City/Town, Urban–Rural Integration Zone, Rural, Special Zone), education (ranging from No Formal Education (Illiterate) to Doctoral Degree/Ph.D.), smoking status (Still Smoke, Quit or No, Never Smoked), drinking status (Drink more than once a month, Drink but less than once a month, None), as well as hypertension, diabetes, and dyslipidemia. For age, middle-aged individuals were defined as those aged 45 to below 60 years, while older adult individuals were defined as those aged 60 years and above. Regarding hypertension, as per the 2010 Chinese Hypertension Guidelines, hypertension was diagnosed based on an average systolic blood pressure ≥ 140mmHg, and/or an average diastolic blood pressure ≥ 90mmHg, and/or self-reported use of antihypertensive medications within the past 2 weeks (28). Diabetes diagnosis criteria included a fasting blood glucose level ≥ 7.0 mmol/L or current treatment with antidiabetic medication. Dyslipidemia diagnosis criteria, following the 2016 Chinese Adult Dyslipidemia Guidelines, included total cholesterol level ≥ 240 mg/dL, high-density lipoprotein cholesterol level < 40 mg/dL, low-density lipoprotein cholesterol level > 160 mg/dL, or triglyceride level ≥ 200 mg/dL (29).

2.5 Statistical analysis

In the demographic characteristics analysis, continuous variables such as age and BI were summarized using mean and standard deviation (SD), while categorical variables like gender, residence, and education were represented as counts and percentages. To examine demographic characteristics, independent sample *t*-tests were employed for continuous variables to discern differences, while chi-square tests were utilized for categorical variables. Correlation analysis involved Pearson correlation tests to assess the relationship between independent variables, covariates, and dependent variables. Subsequently, a comprehensive evaluation of the relationship between ADL and EPs was conducted through hierarchical multiple linear regression analysis. This regression underwent three iterations with distinct models, incorporating dummy variables as references in each variable. Model 1 included three variables: age, gender, and ADL. Model 2 extended Model 1 by adding residence, education, smoking status, and drinking status, resulting in a total of seven variables. Model 3 further expanded upon Model 2 with the inclusion of hypertension, diabetes, and dyslipidemia, encompassing a total of 10 variables.

2.6 Machine learning algorithm

2.6.1 Parameter setup

The machine learning algorithms were implemented using the PyCharm 2023.1.2 integrated development environment and executed on a computer running the Windows 11 operating system. The software development process was conducted within the specified Anaconda development environment, utilizing Python version 3.10.2 for coding and analysis. A random seed number of 42 was set and maintained consistently across the entire process to ensure the reproducibility and consistency of results. The original dataset was partitioned into two distinct subsets: a training set and a testing set. The training set comprised 70% of the original data, while the remaining 30% was allocated to the testing set. The data was randomly shuffled, and the model's performance was evaluated by examining the classification results generated from the testing dataset.

TABLE 1 Activities of daily living scale.

Activities of daily living	Independent	Partially independent	Moderately dependent	Totally dependent
Feeding	10	5	0	0
Bathing	5	0	0	0
Grooming	5	0	0	0
Dressing	10	5	0	0
Transfers	15	10	5	0
Mobility	15	10	5	0
Stairs	10	5	0	0
Toilet Use	10	5	0	0
Bowel Control	10	5	0	0
Bladder Control	10	5	0	0

2.6.2 Experimental models

2.6.2.1 Support vector machine

The SVM stands out as a prominent supervised learning technique within the realm of machine learning, classified as a generalized linear classifier. Its core objective revolves around accurately classifying data points by discerning the maximum-margin hyperplane, which serves as the decision boundary for the training dataset. One of SVM's distinguishing features is its adaptability in tackling nonlinear classification tasks, facilitated by the utilization of kernel functions. This capability underscores SVM's pivotal role in kernel-based learning methodologies. Notably, SVM demonstrates remarkable efficacy in addressing high-dimensional problems, including those characterized by expansive feature spaces, and exhibits prowess in navigating intricate relationships among nonlinear features (30, 31).

2.6.2.2 Decision tree learning

DT, a widely used supervised technique in statistics, data mining, and machine learning, offers versatile classification and regression capabilities. These trees, fashioned as predictive models, derive insights from observational data. In classification, they serve as tree-based models for discrete target variable values, with terminal nodes denoting class labels and branches delineating feature combinations leading to these labels. In regression, decision trees adeptly handle continuous target variable values, typically real numbers. Their adaptability spans various data types, encompassing categorical sequences, thereby augmenting their versatility across diverse analytical domains. Known for their simplicity and interpretability, decision trees are valuable tools for transparent decision-making processes and are particularly useful in decision analysis and data mining applications, where they provide descriptive insights and aid in decision-making (32–34).

2.6.2.3 Logistic regression

LR (Equation 1), a widely embraced methodology in supervised learning within machine learning, is distinct from linear regression as it primarily tackles classification problems, even in multi-classification scenarios. During training, the model learns from a dataset comprising multiple groups, known as the training set, absorbing patterns crucial for classification decisions. After training, the model applies this acquired knowledge to classify one or more datasets, referred to as the test set, each characterized by various indicators contributing to the decision-making process. Logistic regression's adaptability renders it indispensable in supervised learning, playing a foundational role in machine learning methodologies across scientific and medical domains (35–37).

$$\boldsymbol{sigmoid} = \frac{\mathbf{1}}{\mathbf{1} + e^{-z}} \tag{1}$$

Equation 1: Logistic regression.

2.6.3 Evaluating indicator

This study utilized accuracy, precision, recall, and F1-score as the selected evaluation metrics (38, 39). Accuracy assesses the proportion of correctly predicted labels to the total labels (Equation 2). Precision evaluates the proportion of true positive predictions among all positive predictions (Equation 3). Recall gauges the proportion of true positive predictions among all actual positive instances (Equation 4). F1-score reflects the robustness of the model, simultaneously considering precision and recall. A higher F1 value indicates better model performance (Equation 5).

$$\boldsymbol{Accuracy} = \frac{\boldsymbol{TP + TN}}{\boldsymbol{TP + FP + TN + FN}} \tag{2}$$

Equation 2: Accuracy.

$$\boldsymbol{Precision} = \frac{\boldsymbol{TP}}{\boldsymbol{TP + FP}} \tag{3}$$

Equation 3: Precision.

$$\boldsymbol{Recall} = \frac{\boldsymbol{TP}}{\boldsymbol{TP + FN}} \tag{4}$$

Equation 4: Recall.

$$\boldsymbol{F1} = \frac{\boldsymbol{2TP}}{\boldsymbol{2TP + FN + FP}} = \frac{\boldsymbol{2 * Precision * Recall}}{\boldsymbol{Precision + Recall}} \tag{5}$$

Equation 5: F1-score (TP, True Positive; FP, False Positive; FN, False Negative; TN, True Negative).

3 Results

3.1 Characteristics of samples

The study rigorously excluded ineligible subjects, namely those aged 45 and below, as well as individuals lacking adequate demographic or health data. Ultimately, the cohort comprised 9,766 participants, among whom 3,904 were male (39.98%) and 5862 were female (60.02%). Table 2 encapsulates the demographic characteristics of the study cohort, wherein 9539 individuals (97.68%) remained undiagnosed with EPs by medical professionals, while 227 individuals (2.32%) received EP diagnoses. Remarkably, those diagnosed with EPs demonstrated substantially lower average BI scores (65.044, standard deviation = 30.6421) compared to their undiagnosed counterparts (85.128, standard deviation = 17.6386), indicating a significant disparity ($p < 0.001$, $t = 16.573$) in ADL between the diagnosed and undiagnosed EP cohorts. Furthermore, significant differences ($p < 0.001$) were discerned between individuals diagnosed with EPs and those without in terms of gender ($p = 0.015$), smoking status ($p = 0.005$), alcohol consumption ($p < 0.001$), hypertension ($p = 0.001$), and dyslipidemia ($p = 0.011$). Analysis of the demographic features of the sample underscores the influence of ADL, gender, education, smoking and alcohol habits, as well as the presence of hypertension or dyslipidemia on the prevalence of EPs.

3.2 The correlation between variable and EPs

We employed Pearson correlation analysis to explore the relationship between EPs and both independent and covariate variables (Table 3). The results reveal a significant negative correlation between ADL and EPs ($r = -0.165$, $p < 0.001$), indicating an increased susceptibility to EPs among individuals with impaired ADL. Additionally, a slight yet significant positive correlation was observed between gender and EPs ($r = 0.025$, $p = 0.015$), suggesting a higher likelihood of females being diagnosed with EPs. Regarding smoking status, a significant positive correlation with EPs was found ($r = 0.032$, $p = 0.002$), implying a higher susceptibility to EPs among non-smokers. Similarly, a significant positive correlation was observed between alcohol consumption and EPs ($r = 0.044$, $p < 0.001$), indicating that individuals with lower alcohol consumption frequency are more likely to be diagnosed with EPs. Furthermore, hypertension ($r = 0.032$, $p = 0.001$) and dyslipidemia ($r = 0.026$, $p = 0.011$) exhibited significant positive correlations with EPs, suggesting a greater likelihood of individuals with hypertension or dyslipidemia being diagnosed with EPs.

3.3 Associations between ADL and EPs

To delve deeper into the correlation between EPs and ADL, we employed hierarchical multiple linear regression to systematically investigate the association between the independent variables (ADL, age, gender, residence, smoking status, etc.) and the dependent variable EPs across three distinct models (Model 1, Model 2, Model 3; Table 4).

In Model 1, we included ADL, age, and gender ($R = 0.170$, $R^2 = 0.029$, $F = 96.764$, $p < 0.001$). We observed a significant negative correlation between ADL and EPs ($B = -0.001$, $\beta = -0.175$, $t = -16.777$, 95% CI $= -0.002$, -0.001, $p = 0.000$), underscoring the heightened susceptibility to EPs among individuals with impaired daily living abilities. In Model 2, additional covariates were incorporated (residence, education, smoking, and drinking status), where ADL continued to exhibit a pronounced negative correlation with EPs ($B = -0.001$, $\beta = -0.174$, $t = -16.528$, 95% CI $= -0.002$, -0.001, $p = 0.000$), maintaining statistical significance. In the final iteration, Model 3 introduced hypertension, dyslipidemia, and diabetes, reaffirming the negative correlation between ADL and EPs ($B = -0.002$, $\beta = -0.186$, $t = -16.476$, 95% CI $= -0.002$, -0.001, $p = 0.000$), with an overall significant fit ($R = 0.190$, $R^2 = 0.036$, $F = 15.870$, $p < 0.001$).

All three models demonstrated statistically significant associations between the independent and dependent variables ($p < 0.001$). The R value increased gradually from 0.170 in Model 1 to 0.190 in Model 3, indicating an enhanced ability to explain the variability of outcomes. Across all models, despite adjustments for covariates, our study consistently emphasized the significant association between declining ADL and increased susceptibility to EPs, while underscoring the robustness of this relationship.

In our investigation, hypertension emerged as a consistent factor exhibiting correlation with EPs across all analyses, suggesting its potential role as a significant confounding factor in this study. To mitigate this confounding effect, we partitioned the entire sample into two cohorts: a hypertension group (Table 5) and a non-hypertension group (Table 6). Through this stratification, we aimed to delve into the relationship between ADL and EPs in detail.

Within the hypertension group, iterative modeling across three iterations continued to reveal a statistically significant negative correlation between ADL and EPs ($B = -0.001$, $\beta = -0.123$, $t = -4.784$, 95% CI $= -0.001$, -0.001, $p = 0.000$). Similarly, within the non-hypertension group, this negative correlation persisted ($B = -0.002$, $\beta = -0.202$, $t = -17.450$, 95% CI $= -0.002$, -0.002, $p = 0.000$). These findings underscore that irrespective of hypertension status and adjustments for covariates, ADL continues to influence susceptibility to EPs ($p < 0.001$).

3.4 Machine learning algorithm confirm the link between ADL and EPs

Through statistical analysis, we have identified a significant negative correlation between ADL and EPs, indicating that individuals with impaired daily living abilities are more susceptible to EPs. Moreover, employing hierarchical multiple linear regression, adjusting for and iterating covariates, we have established the stability of the negative correlation between ADL and EPs. Consequently, we employed three machine learning algorithms—SVM, DT, and LR—to validate the association between the two.

The results (see Figure 1A) demonstrate that the Area Under the Curve (AUC) values of SVM, DT, and LR exceeded the critical threshold of 0.7, reaching 0.700, 0.742, and 0.711, respectively, confirming the diagnostic capability of these models. Comprehensive evaluation of the three machine learning algorithms using Accuracy, Precision, Recall, and F1 Score metrics (see Figure 1B; Table 7) reveals that DT exhibited outstanding Accuracy (0.677) and Precision (0.735), while SVM demonstrated superiority in Recall (0.600) and F1 Score (0.637). The combined statistical analysis and machine learning algorithm validation affirm a substantial association between ADL and EPs, indicating that impaired daily living abilities increase susceptibility to emotional problems.

To enhance the credibility of the association between ADL and EPs and underscore the predictive role of ADL in EPs, we partitioned the dataset into two groups with distinct features. The first group included all covariates except for the Bath Index (BI), while the second group incorporated BI while retaining the same set of covariates. Machine learning algorithms rigorously validated these two data subsets. The results demonstrate that upon inclusion of BI, the AUC values of SVM and LR models increased from 0.825 and 0.627 to 0.903 and 0.743, respectively, whereas in the DT model, the AUC value decreased from 0.966 to 0.956. Overall, the addition of BI enhanced the predictive AUC values and improved model performance (see Figures 2A,B). Further analysis using Accuracy, Precision, Recall, and F1 Score metrics (see Figures 2C–E; Table 8) revealed that the SVM model exhibited the best performance, with Accuracy increasing from 0.749 to 0.823, Precision from 0.698 to 0.794, and F1 Score from 0.776 to 0.830, demonstrating robust overall performance.

All three machine learning algorithms verified the association between ADL and EPs and affirmed the positive role of BI in overall prediction, enhancing model performance. The validation of machine learning algorithms confirms our finding that impaired daily living abilities increase susceptibility to EPs.

TABLE 2 Demographic characteristics of middle-aged and older adults Chinese with and without emotional problems by doctor.

Variables	Not diagnosed with emotional problems by a doctor	Diagnosed with emotional problems by a doctor	*p*-value	t/χ^2
No. subjects (%)	9539(97.68)	227(2.32)		
Age, year			0.157	1.415
	65.14267743	66.1277533		
SD	10.36763582	10.15416304		
Gender, n (%)			0.015	5.918
Male	3831(40.16)	73(32.16)		
Female	5708(59.84)	154(67.84)		
Residence, n (%)			0.105	6.150
Central of City/Town	1614(16.92)	35(15.42)		
Urban–Rural Integration Zone	628(6.58)	24(10.57)		
Rural	7274(76.26)	167(73.57)		
Special Zone	23(0.24)	1(0.44)		
Education, n (%)				
No Formal Education (Illiterate)	2083(21.84)	51(22.47)	<0.001	44.91
Did not Finish Primary School	1839(19.28)	39(17.18)		
Sishu/Home School	18(0.19)	1(0.44)		
Elementary School	2016(21.13)	50(22.03)		
Middle School	2172(22.77)	53(23.35)		
High School	856(8.97)	19(8.37)		
Vocational School	282(2.96)	8(3.52)		
Two-/Three-Year College/Associate Degree	157(1.65)	4(1.76)		
Four-Year College/Bachelor's Degree	105(1.10)	1(0.44)		
Master's Degree	11(0.12)	0(0)		
Doctoral Degree/Ph.D.	0(0)	1(0.44)		
Smoking status, n (%)			0.005	10.713
Still Smoke	2131(22.34)	30(13.22)		
Quit or No	7293(76.45)	194(85.46)		
Never Smoked	115(1.21)	3(1.32)		
Drinking status, n (%)			<0.001	21.67
Drink more than once a month	1895(19.87)	23(10.13)		
Drink less than once a month	630(6.60)	6(2.64)		
None	7014(73.53)	198(87.22)		
Hypertension, n (%)				
Yes	1799(18.86)	62(27.31)	0.001	10.272
No	7740(81.14)	165(72.69)		
Diabetes, n (%)				
Yes	650(6.81)	18(7.93)	0.511	0.433
No	8889(93.19)	209(92.07)		
Dyslipidemia, n (%)				
Yes	1256(13.17)	43(18.94)	0.011	6.414
No	8283(86.83)	184(81.06)		
Activity of daily living (The Barthel Index)			<0.001	−16.573
	85.128	65.044		
SD	17.6386	30.6421		

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TABLE 3 Correlation between variable and emotional problems.

Variables	Emotional problems	
	r	*p*-value
Age	0.014	0.157
Gender	0.025	0.015
Residence	−0.002	0.878
Education	0.002	0.842
Smoking status	0.032	0.002
Drinking status	0.044	<0.001
Hypertension	0.032	0.001
Diabetes	0.007	0.511
Dyslipidemia	0.026	0.011
Activity of daily living(The Barthel Index)	−0.165	<0.001

Emotional problems: 0 = "Not diagnosed with Emotional Problems by a Doctor," 1 = "Diagnosed with Emotional Problems by a Doctor"; Gender:1 = "Male,"2 = "Female";Residence:1 = "Central of City/Town ",2 = "Urban–Rural Integration Zone,"3 = "Rural,"4 = "Special Zone";Education:1 = "No Formal Education (Illiterate),"2 = "Did not Finish Primary School,"3 = "Sishu/Home School,"4 = "Elementary School,"5 = "Middle School,"6 = "High School,"7 = "Vocational School,"8 = "Two-/Three-Year College/Associate Degree,"9 = "Four-Year College/Bachelor's Degree,"10 = "Master's Degree,"11 = "Doctoral Degree/Ph.D."; Smoking status:1 = "Still Smoke,"2 = "Quit or No,"3 = "Never Smoked"; Drinking status:1 = "Drink More than Once a Month,"2 = "Drink But Less than Once a Month," 3 = "None"; Hypertension/Diabetes/Dyslipidemia:0 = "No,"1 = "Yes."

4 Discussion

Amidst the ongoing global aging population phenomenon (40), the potential hazards of EPs among middle-aged and older adult individuals are gradually gaining attention. EPs may arise from psychological discrepancies associated with aging and are often concomitant with certain diseases (41). The exacerbation of global aging has led to increased feelings of loneliness among the older adult, coupled with the disregard for psychological well-being and emotional stability by individuals and families, thereby fostering the proliferation of EPs (42, 43). Hence, early detection and intervention for the complex factors contributing to EPs become particularly imperative.

In this study, we commenced by conducting demographic analyses of the individuals included in the research cohort. We observed disparities in the mean BI scores between cohorts afflicted with EPs and those without EPs, with the former exhibiting lower mean BI scores compared to the latter. Subsequently, utilizing Pearson correlation analysis, we established a negative correlation between ADL and EPs. Subsequent to this, employing iterative iterations of three distinct models, we conducted stratified multivariate linear regression. Even after controlling for covariates such as age, gender, residency, education, smoking and drinking status, and chronic diseases, a significant negative correlation between ADL and EPs persisted. Furthermore, machine learning algorithms validated our findings. In experiments utilizing solely BI data, the AUC scores of all three machine learning algorithms exceeded 0.7, indicating diagnostic value. In the subsequent experiments involving two groups—one with additional covariates and another with additional covariates plus BI—the inclusion of BI resulted in an overall enhancement of the predictive performance of machine learning algorithms. Particularly noteworthy was the notable improvement observed in the predictive performance of SVM when BI was added. This underscores the positive influence of BI on the predictive capabilities of machine learning algorithms, thus corroborating our findings that ADL impairment heightens susceptibility to EPs.

This study also conducted an analysis of other covariates. In the examination of demographic characteristics and Pearson correlation, gender, smoking and drinking status, hypertension, and dyslipidemia exhibited statistically significant differences between the EPs and non-EPs groups and were all significantly positively correlated with EPs. Specifically, females were more prone to EPs, while individuals with hypertension and dyslipidemia were also more susceptible to EPs, consistent with previous research findings (44–48). However, regarding smoking and drinking status, the results of this study showed that individuals who smoked less and drank less frequently were more susceptible to EPs, contradicting previous studies. We attribute this discrepancy to the higher proportion of female individuals in this study, as generally, fewer Chinese females have habits of smoking and drinking in daily life (49, 50). Additionally, studies have reported that acetylcholine contributes to regulating brain homeostasis and shaping synaptic neuron transmission and neurotransmitter levels (51). Nicotine may improve mood and alleviate anxiety by increasing acetylcholine release and the number of nicotinic receptors (52). As for other covariates such as residence and education level in this study, their definitions cannot be simply delineated through basic demographic characteristics and Pearson correlation analysis. These factors, as potential influencers of EPs, may require joint analysis with various socio-economic factors such as offspring support, retirement pensions, family migration, childhood experiences, etc., to derive more scientifically sound conclusions (53).

This study identified a significant negative correlation between ADL and EPs, which remained stable even after adjusting for other covariates, a relationship confirmed by machine learning algorithms. Therefore, emphasizing the importance of exercise for the older adults in daily life activities is crucial. Encouraging the older adults to improve ADL in community healthcare and home care settings serves as a preventive measure against EPs and ensures a better quality of life, forming the basis for quality longevity (54, 55). In the process of disease rehabilitation, such as stroke, timely restoration of ADL in patients is conducive to their psychological well-being post-illness and enhances their confidence in recovery (56, 57).

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TABLE 4 Associations between ADL and emotional problems in middle-aged and older adults Chinese.

Model	R	R square	F	*p*-value	Variables		B	*β*	*t*	95%CI		*p*-value
Model 1	0.170	0.029	96.764	<0.001		ADL	−0.001	−0.175	−16.777	−0.002	−0.001	0.000
						Age	−0.001	−0.036	−3.446	−0.001	0.000	0.001
					Gender	Male	−0.005	−0.015	−1.489	−0.011	0.001	0.137
						Female(Ref.)						
Model 2	0.187	0.035	17.752	<0.001		ADL	−0.001	−0.174	−16.528	−0.002	−0.001	0.000
						Age	−0.001	−0.037	−3.553	−0.001	0.000	0.000
					Gender	Male	0.000	0.000	−0.013	−0.007	0.007	0.990
						Female(Ref.)						
					Residence	Central of City/Town	−0.018	−0.044	−0.576	−0.077	0.042	0.564
						Urban–Rural Integration Zone	−0.004	−0.007	−0.138	−0.065	0.056	0.890
						Rural	−0.023	−0.065	−0.758	−0.082	0.036	0.448
						Special Zone(Ref.)						
					Education	No Formal Education (Illiterate)	−0.966	−2.648	−6.514	−1.256	−0.675	0.000
						Did not Finish Primary School	−0.969	−2.534	−6.536	−1.259	−0.678	0.000
						Sishu/Home School	−0.936	−0.274	−6.157	−1.234	−0.638	0.000
						Elementary School	−0.965	−2.616	−6.511	−1.256	−0.675	0.000
						Middle School	−0.966	−2.688	−6.515	−1.256	−0.675	0.000
						High School	−0.969	−1.836	−6.533	−1.259	−0.678	0.000
						Vocational School	−0.963	−1.085	−6.485	−1.254	−0.672	0.000
						Two-/Three-Year College/Associate Degree	−0.969	−0.819	−6.521	−1.261	−0.678	0.000
						Four-Year College/Bachelor’s Degree	−0.978	−0.672	−6.565	−1.269	−0.686	0.000
						Master’s Degree	−0.981	−0.218	−6.338	−1.285	−0.678	0.000
						Doctoral Degree/Ph.D.(Ref.)						
					Smoking status	Still Smoke	−0.006	−0.016	−0.420	−0.033	0.022	0.674
						Quit or No	−0.002	−0.005	−0.131	−0.029	0.025	0.895
						Never Smoked(Ref.)						
					Drinking status	Drink more than once a month	−0.007	−0.020	−1.759	−0.016	0.001	0.079
						Drink less than once a month	−0.013	−0.021	−2.033	−0.025	0.000	0.042
						No(Ref.)						

(Continued)

TABLE 4 (Continued)

Model	R	R square	F	*p*-value	Variables		B	*β*	*t*	95%CI		*p*-value
Model 3	0.190	0.036	15.870	<0.001		ADL	−0.002	−0.186	−16.476	−0.002	−0.001	0.000
						Age	−0.001	−0.037	−3.535	−0.001	0.000	0.000
					Gender	Male	0.000	0.000	0.041	−0.007	0.008	0.968
						Female(Ref.)						
					Residence	Central of City/Town	−0.017	−0.043	−0.567	−0.077	0.042	0.571
						Urban–Rural Integration Zone	−0.004	−0.006	−0.123	−0.064	0.057	0.902
						Rural	−0.023	−0.065	−0.761	−0.082	0.036	0.446
						Special Zone(Ref.)						
					Education	No Formal Education (Illiterate)	−0.963	−2.641	−6.499	−1.254	−0.673	0.000
						Did not Finish Primary School	−0.966	−2.528	−6.521	−1.257	−0.676	0.000
						Sishu/Home School	−0.932	−0.273	−6.130	−1.230	−0.634	0.000
						Elementary School	−0.963	−2.609	−6.497	−1.253	−0.672	0.000
						Middle School	−0.963	−2.682	−6.501	−1.254	−0.673	0.000
						High School	−0.966	−1.831	−6.517	−1.257	−0.675	0.000
						Vocational School	−0.960	−1.082	−6.471	−1.251	−0.669	0.000
						Two-/Three-Year College/Associate Degree	−0.967	−0.817	−6.506	−1.258	−0.676	0.000
						Four-Year College/Bachelor's Degree	−0.975	−0.671	−6.553	−1.267	−0.684	0.000
						Master's Degree	−0.977	−0.217	−6.310	−1.280	−0.673	0.000
						Doctoral Degree/Ph.D.(Ref.)						
					Smoking status	Still Smoke	−0.007	−0.019	−0.488	−0.034	0.021	0.626
						Quit or No	−0.003	−0.008	−0.197	−0.030	0.024	0.844
						Never Smoked(Ref.)						
					Drinking status	Drink more than once a month	−0.008	−0.020	−1.813	−0.016	0.001	0.070
						Drink less than once a month	−0.012	−0.020	−2.016	−0.025	0.000	0.044
						No(Ref.)						
					Hypertension	Yes	−0.012	−0.030	−2.781	−0.020	−0.003	0.005
						No(Ref.)						
					Diabetes	Yes	−0.007	−0.011	−1.104	−0.019	0.005	0.270
						No(Ref.)						
					Dyslipidemia	Yes	0.000	0.000	0.026	−0.009	0.009	0.979
						No(Ref.)						

TABLE 5 Associations between ADL and EPs in the hypertension group.

Model	R	R square	F	*p*-value	Variables		B	*β*	*t*	95%CI		P-value
Model 1	0.134	0.018	11.301	<0.001		ADL	−0.001	−0.141	−5.750	−0.001	−0.001	0.000
						Age	−0.001	−0.053	−2.171	−0.002	0.000	0.030
					Gender	Male	−0.005	−0.014	−0.591	−0.021	0.012	0.554
						Female(Ref.)						
Model 2	0.156	0.024	2.430	<0.001		ADL	−0.001	−0.130	−5.141	−0.001	−0.001	0.000
						Age	−0.001	−0.057	−2.293	−0.002	0.000	0.022
					Gender	Male	0.006	0.017	0.628	−0.013	0.026	0.530
						Female(Ref.)						
					Residence	Central of City/Town	0.027	0.055	0.297	−0.150	0.204	0.767
						Urban–Rural Integration Zone	0.050	0.071	0.544	−0.129	0.228	0.586
						Rural	0.032	0.075	0.353	−0.144	0.208	0.724
						Special Zone(Ref.)						
					Education	No Formal Education (Illiterate)	0.020	0.046	0.225	−0.156	0.196	0.822
						Did not Finish Primary School	0.025	0.055	0.274	−0.152	0.201	0.784
						Sishu/Home School	−0.004	−0.001	−0.039	−0.230	0.222	0.969
						Elementary School	0.024	0.054	0.263	−0.153	0.200	0.793
						Middle School	0.034	0.078	0.381	−0.142	0.210	0.703
						High School	0.019	0.031	0.206	−0.159	0.196	0.837
						Vocational School	0.028	0.026	0.300	−0.154	0.209	0.764
						Two-/Three-Year College/Associate Degree	0.047	0.035	0.494	−0.139	0.232	0.622
						Four-Year College/Bachelor's Degree	−0.006	−0.003	−0.061	−0.202	0.190	0.951
						Doctoral Degree/Ph.D.(Ref.)						
					Smoking status	Still Smoke	0.032	0.070	0.943	−0.034	0.097	0.346
						Quit or No	0.042	0.097	1.285	−0.022	0.106	0.199
						Never Smoked(Ref.)						
					Drinking status	Drink more than once a month	−0.022	−0.045	−1.742	−0.046	0.003	0.082
						Drink less than once a month	−0.031	−0.041	−1.723	−0.066	0.004	0.085
						No(Ref.)						

(Continued)

TABLE 5 (Continued)

Model	R	R square	F	*p*-value	Variables		B	*β*	*t*	95%CI		P-value
Model 3	0.163	0.026	2.383	<0.001		ADL	−0.001	−0.123	−4.784	−0.001	−0.001	0.000
						Age	−0.001	−0.052	−2.085	−0.002	0.000	0.037
					Gender	Male	0.005	0.014	0.504	−0.015	0.025	0.614
						Female(Ref.)						
					Residence	Central of City/Town	0.023	0.047	0.256	−0.154	0.200	0.798
						Urban–Rural Integration Zone	0.045	0.064	0.494	−0.134	0.223	0.622
						Rural	0.029	0.070	0.328	−0.147	0.205	0.743
						Special Zone(Ref.)						
					Education	No Formal Education (Illiterate)	0.018	0.041	0.201	−0.158	0.194	0.841
						Did not Finish Primary School	0.022	0.048	0.242	−0.154	0.198	0.808
						Sishu/Home School	−0.007	−0.002	−0.065	−0.233	0.219	0.948
						Elementary School	0.021	0.049	0.238	−0.155	0.197	0.812
						Middle School	0.032	0.072	0.352	−0.144	0.208	0.725
						High School	0.016	0.027	0.178	−0.161	0.193	0.859
						Vocational School	0.027	0.026	0.292	−0.154	0.208	0.770
						Two-/Three-Year College/Associate Degree	0.043	0.032	0.460	−0.142	0.229	0.646
						Four-Year College/Bachelor's Degree	−0.010	−0.005	−0.101	−0.206	0.186	0.920
						Master's Degree(Ref.)						
					Smoking status	Still Smoke	0.033	0.073	0.978	−0.033	0.099	0.328
						Quit or No	0.042	0.097	1.289	−0.022	0.107	0.198
						Never Smoked(Ref.)						
					Drinking status	Drink more than once a month	−0.022	−0.045	−1.762	−0.046	0.002	0.078
						Drink less than once a month	−0.030	−0.040	−1.704	−0.065	0.005	0.089
						No(Ref.)						
					Diabetes	Yes	−0.015	−0.028	−1.195	−0.040	0.010	0.232
						No(Ref.)						
					Dyslipidemia	Yes	0.017	0.043	1.766	−0.002	0.036	0.078
						No(Ref.)						

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TABLE 6 Associations between ADL and EPs in the non-hypertension group.

Model	R	R square	F	*p*-value	Variables		B	*β*	*t*	95%CI		*p*-value
Model 1	0.193	0.037	102.236	<0.001		ADL	−0.002	−0.198	−17.273	−0.002	−0.002	0.000
						Age	0.000	−0.033	−2.877	−0.001	0.000	0.004
					Gender	Male	−0.004	−0.014	−1.294	−0.011	0.002	0.196
						Female(Ref.)						
Model 2	0.202	0.041	17.672	<0.001		ADL	−0.002	−0.201	−17.403	−0.002	−0.002	0.000
						Age	−0.001	−0.036	−3.149	−0.001	0.000	0.002
					Gender	Male	−0.001	−0.004	−0.278	−0.009	0.007	0.781
						Female(Ref.)						
					Residence	Central of City/Town	−0.028	−0.073	−0.875	−0.090	0.034	0.382
						Urban–Rural Integration Zone	−0.018	−0.031	−0.552	−0.080	0.045	0.581
						Rural	−0.037	−0.110	−1.176	−0.099	0.025	0.240
						Special Zone(Ref.)						
					Education	No Formal Education (Illiterate)	−0.107	−0.309	−2.148	−0.204	−0.009	0.032
						Did not Finish Primary School	−0.112	−0.308	−2.254	−0.209	−0.015	0.024
						Sishu/Home School	−0.047	−0.013	−0.751	−0.171	0.076	0.453
						Elementary School	−0.108	−0.307	−2.163	−0.205	−0.010	0.031
						Middle School	−0.111	−0.326	−2.224	−0.208	−0.013	0.026
						High School	−0.111	−0.219	−2.221	−0.209	−0.013	0.026
						Vocational School	−0.104	−0.124	−2.066	−0.203	−0.005	0.039
						Two-/Three-Year College/Associate Degree	−0.119	−0.105	−2.330	−0.219	−0.019	0.020
						Four-Year College/Bachelor's Degree	−0.117	−0.087	−2.265	−0.219	−0.016	0.024
						Master's Degree(Ref.)						
					Smoking status	Still Smoke	−0.022	−0.064	−1.418	−0.052	0.008	0.156
						Quit or No	−0.019	−0.057	−1.261	−0.049	0.011	0.207
						Never Smoked(Ref.)						
					Drinking status	Drink more than once a month	−0.005	−0.015	−1.166	−0.014	0.004	0.244
						Drink less than once a month	−0.009	−0.016	−1.413	−0.022	0.004	0.158
						No(Ref.)						

(Continued)

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TABLE 6 (Continued)

Model	R	R square	F	*p*-value	Variables		B	*β*	*t*	95%CI		*p*-value
Model 3	0.203	0.041	16.081	<0.001		ADL	−0.002	−0.202	−17.450	−0.002	−0.002	0.000
						Age	−0.001	−0.037	−3.219	−0.001	0.000	0.001
					Gender	Male	−0.001	−0.004	−0.275	−0.009	0.007	0.783
						Female(Ref.)						
					Residence	Central of City/Town	−0.028	−0.073	−0.880	−0.090	0.034	0.379
						Urban–Rural Integration Zone	−0.018	−0.031	−0.553	−0.080	0.045	0.580
						Rural	−0.037	−0.111	−1.189	−0.099	0.024	0.235
						Special Zone(Ref.)						
					Education	No Formal Education (Illiterate)	−0.106	−0.306	−2.132	−0.203	−0.009	0.033
						Did not Finish Primary School	−0.111	−0.306	−2.237	−0.209	−0.014	0.025
						Sishu/Home School	−0.047	−0.013	−0.748	−0.171	0.076	0.455
						Elementary School	−0.107	−0.305	−2.149	−0.204	−0.009	0.032
						Middle School	−0.110	−0.324	−2.209	−0.207	−0.012	0.027
						High School	−0.110	−0.218	−2.208	−0.208	−0.012	0.027
						Vocational School	−0.104	−0.123	−2.053	−0.202	−0.005	0.040
						Two-/Three-Year College/Associate Degree	−0.118	−0.104	−2.312	−0.218	−0.018	0.021
						Four-Year College/Bachelor’s Degree	−0.116	−0.086	−2.250	−0.218	−0.015	0.024
						Master’s Degree(Ref.)						
					Smoking status	Still Smoke	−0.022	−0.065	−1.438	−0.052	0.008	0.151
						Quit or No	−0.019	−0.058	−1.278	−0.049	0.010	0.201
						Never Smoked(Ref.)						
					Drinking status	Drink more than once a month	−0.005	−0.015	−1.207	−0.014	0.003	0.227
						Drink less than once a month	−0.009	−0.016	−1.410	−0.022	0.004	0.158
						No(Ref.)						
					Diabetes	Yes	−0.003	−0.005	−0.467	−0.017	0.010	0.641
						No(Ref.)						
					Dyslipidemia	Yes	−0.007	−0.014	−1.255	−0.017	0.004	0.210
						No(Ref.)						

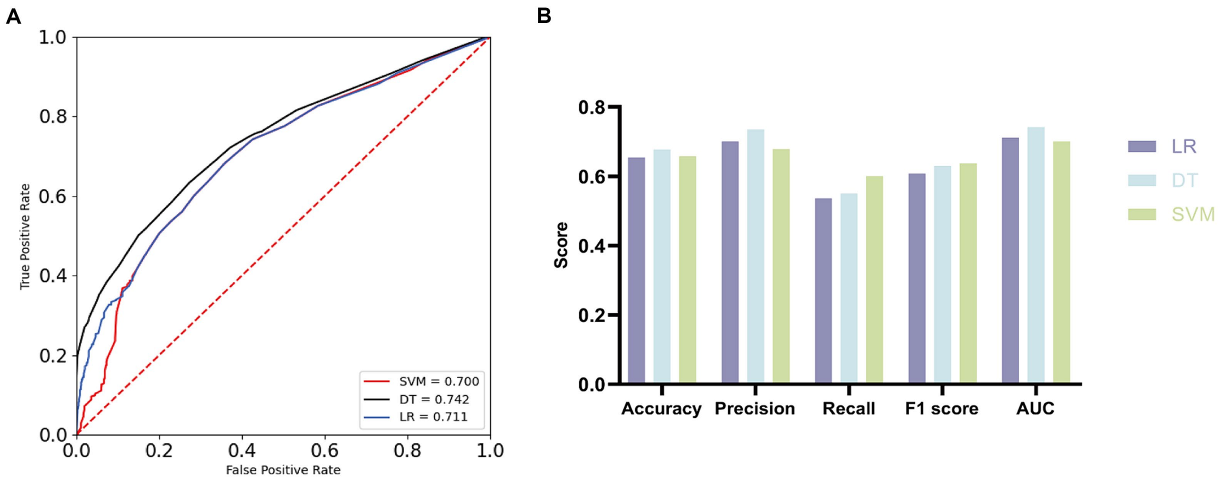

FIGURE 1
Receiver operating characteristic (ROC) curves and evaluation metrics. **(A)** ROC curves with AUC for the three machine learning algorithms. **(B)** Comparison of three machine learning algorithms.

TABLE 7 **Evaluation of the three machine learning algorithms.**

Model	Accuracy	Precision	Recall	F1 score	AUC
SVM	0.658	0.678	0.600	0.637	0.700
DT	0.677	0.735	0.551	0.630	0.742
LR	0.654	0.701	0.536	0.608	0.711

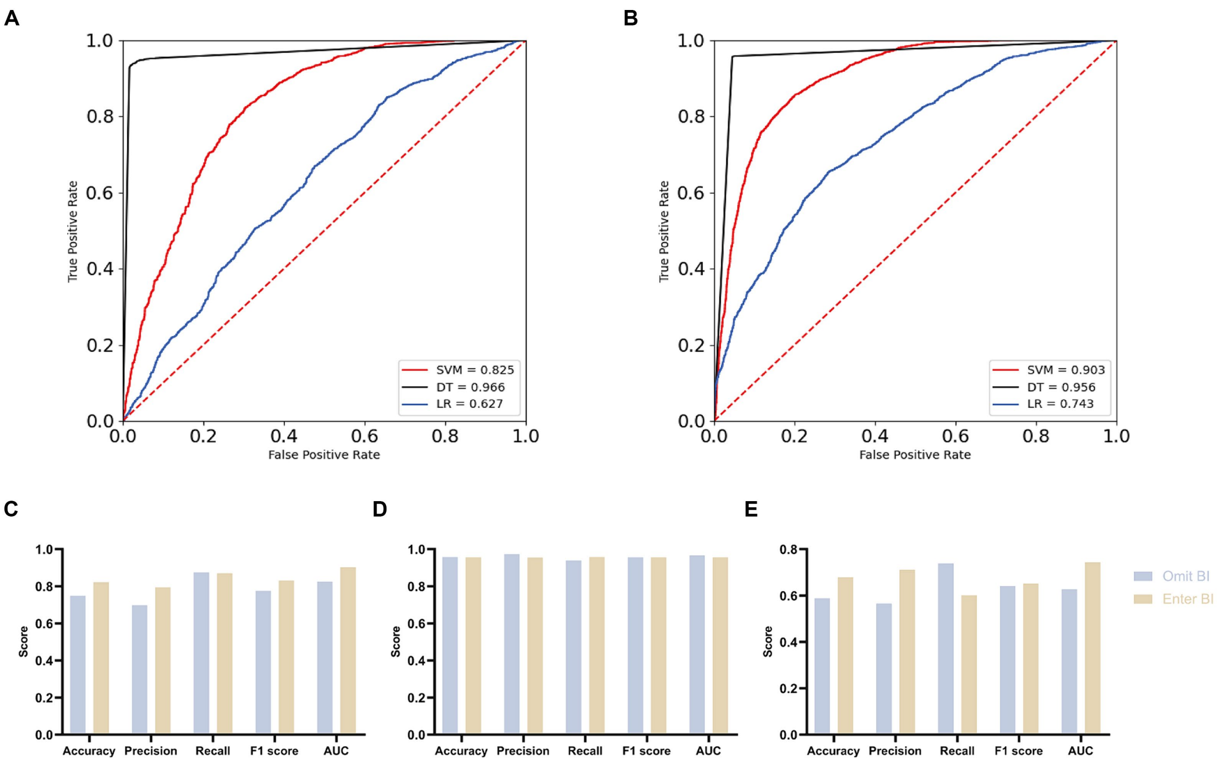

FIGURE 2
Comparison of overall effects of machine learning algorithms for two distinct datasets. **(A)** ROC curves with AUC for omit Barthel index group. **(B)** ROC curves with AUC for enter Barthel index group. **(C)** Contrasting the SVM model across the two groups. **(D)** Contrasting the DT model across the two groups. **(E)** Contrasting the LR model across the two groups.

TABLE 8 Overall evaluation of three machine learning algorithms for two datasets.

Model	Accuracy		Precision		Recall		F1 score		AUC	
	Omit BI	Enter BI	Omit BI	Enter BI	Omit BI	Enter BI	Omit BI	Enter BI	Omit BI	Enter BI
SVM	0.749	0.823	0.698	0.794	0.875	0.870	0.776	0.830	0.825	0.903
DT	0.957	0.956	0.973	0.955	0.939	0.957	0.956	0.956	0.966	0.956
LR	0.588	0.679	0.566	0.711	0.739	0.601	0.641	0.651	0.627	0.743

Nevertheless, this study has limitations. Its cross-sectional design precludes longitudinal exploration, hindering causal relationship establishment between ADL and EPs. Declining ADL may signify a symptom rather than a causative factor in EPs progression, inferring only a significant negative correlation between ADL and EPs. CHARLS data, collected annually, lacks precise diagnosis timings, constraining causal relationship determination. Future longitudinal studies are vital for robust evidence. Relying on "Diagnosed with Emotional Problems by a Doctor" in CHARLS, lacking detailed emotional problem classification such as Posttraumatic Stress Disorder (PTSD) and Generalized Anxiety Disorder (GAD), is another limitation. Enhancing understanding requires comprehensive emotional health assessments. Despite significant ADL-EPs correlation, predictive utility of ADL alone is limited; exploring sleep quality, social support, socioeconomic status, and chronic stress is needed to enhance predictive accuracy. Additionally, the small proportion (2.32%) of individuals diagnosed with EPs may introduce bias. Despite utilizing Synthetic Minority Over-sampling Technique(SMOTE) to address class imbalance, future studies should explore advanced techniques like stratified sampling or ensemble learning algorithms to improve result reliability. Although we examined three machine learning algorithms, further investigation is warranted for optimal predictive model identification. Nonetheless, our study's predictive capacity remains significant (58, 59).. Furthermore, BI, derived from self-reported scales in the CHARLS dataset, differs from clinical assessments. However, literature supports the reliability of self-reported ADL assessments, validating our approach (60–62).

5 Conclusion

This study employs various statistical methods to reveal a negative correlation between ADL and EPs. Furthermore, the utilization of machine learning algorithms confirms this finding, indicating that impaired ADL heightens susceptibility to EPs.

5.1 Summary

Emotional Problems (EPs) have become a significant challenge affecting the quality of life in middle-aged and older adult populations, garnering increasing attention in public health. Early detection of potential EPs among middle-aged and older adults is crucial. This study explores the potential of Activities of Daily Living (ADL) as predictive indicators for EPs. Using data from the 2018 China Health and Retirement Longitudinal Study (CHARLS) national baseline survey, which includes 9,766 individuals aged 45 and above, we assessed ADL using the Barthel Index (BI). Statistical analyses were conducted to investigate the correlation between ADL and EPs, followed by validation using machine learning algorithms (Support Vector Machine, Decision Tree, and Logistic Regression) to elucidate the underlying relationship between ADL and EPs.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by the National School of Development at Peking University (http://charls.pku.edu.cn). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

MG: Conceptualization, Data curation, Writing – original draft, Formal analysis, Investigation, Methodology. SX: Methodology, Software, Validation, Writing – original draft. XH: Data curation, Investigation, Supervision, Writing – original draft. JH: Methodology, Software, Validation, Writing – original draft. HY: Conceptualization, Formal analysis, Project administration, Resources, Writing – review & editing. LZ: Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1391033/full#supplementary-material

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A study protocol for identifying aging trajectories toward chronic neurodegenerative diseases by means of Marche regional administrative databases – TREND project

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Background: People are living longer but an increasing number of older people experience chronicity and disability in the latest years of their life. The Marche region is one of the Italian regions where people live the longest lives; therefore, the number of people with age-related chronic diseases is expected to be at least similar, if not higher, compared to the rest of Italy. The identification of the aging trajectories is of huge interest in the arena of public health. Administrative healthcare databases represent valuable reservoirs for reconstructing the trajectories of aging. Here, we present the protocol for a study (TREND project) aimed to integrate existing administrative databases into a Marche regional dataset in order to estimate the prevalence and incidence rates of age-related neurodegenerative diseases (ND), with a specific focus on Parkinsonism and Dementia.

Methods: The TREND Project is a retrospective cross-sectional study. The source population includes permanent residents in the Marche region aged 40 years and older. A minimal dataset has been built up linking data on drug prescriptions, outpatient services, and diagnosis for hospital admission, from 2014 to 2021 in the Marche Region. Data on clinical outcomes (re-hospitalization, mortality, comorbidities), and therapeutic approaches (drugs and medicines) have been integrated with state-of-the-art statistical methods to define patients into different risk clusters and to analyze the aging trend by assessing the Comorbidity Index (CI) as a proxy for chronicity.

Discussion: Our research contributes to the integration of existing administrative databases on ND to create a Marche regional ND database, support regional health policy, and better understand patients' needs and their aging trajectories. This approach could be implemented also at the National level. Moreover, by linking different administrative data sources, this study sheds light on important issues related to ND, such as early-onset dementia; ethical aspects such as anticipated wills; problems of dementia in patients still in the job market, etc.

The results of this study will contribute to the successful implementation of integrated care for patients affected by ND at regional or national levels.

KEYWORDS

neurodegenerative disease, administrative databases, dementia, Parkinson's disease, geographical information system

1 Introduction

Despite notable advances in diagnosis and therapeutic management, we are still largely unsuccessful at postponing or preventing the chronic complications of the most common age-related diseases, especially neurodegenerative diseases, including Alzheimer disease (AD) and dementia, and Parkinson's disease (PD). In other words, we have been becoming more and more able to increase the life expectancy of our patients, but we were not equally able to improve their quality of life. Although the human average life expectancy in developed countries has increased dramatically, this rise has, indeed, been accompanied by an increase in the prevalence of chronic disorders (1), including neurodegenerative diseases (ND), which in turn are the major causes of disability and mortality.

According to the latest WHO data published in 2020, dementia represented 7.64% of total deaths in Italy (2). The prevalence of dementia, considered in all its forms, is estimated at around 9% in the Italian population over 65 years (3). Likewise, PD, which is the second most common neurodegenerative disorder worldwide after AD, has become more and more frequent due to the increasing life expectancy (4). In fact, from 1990 to 2016, the number of patients with PD globally increased to 6.2 million (5). PD is frequently accompanied by dementia, with a point prevalence of 30% (6).

Considering the strict relationship between the increase in life expectancy and the burden of ND in developed countries, research initiatives aimed at increasing health span and compressing morbidity are of crucial clinical and socio-economical relevance. Such complex multimorbidity is a major challenge to existing models of healthcare delivery and there is a need to ensure integrated care across disease pathways and primary and secondary care (7).

From a gerontology/geriatric point of view, the aging process is the result of the combined effects of selective and remodeling forces toward achieving human longevity (8, 9). From a clinical viewpoint, successful aging can be measured as a multidimensional construct that reflects the complexity and dynamics of many physiological systems (10). Perturbations and, hypothetically, a narrowing of this complexity may reduce the ability to adapt to stress and lead to frailty (11). In this framework, the analysis of care trajectories through the analysis of administrative health databases has been proposed as a tool for population-based estimations and is increasingly being adopted to obtain estimates of the aging process, disease burden, quality of care, and resource allocation (12). Healthcare administrative databases show many advantages, such as ease of access, the wide range of tracked diseases and comorbidities, and the ability to provide both cross-sectional and longitudinal data that can be analyzed and visualized also by the use of Geographical Information Systems (GIS) (13). GIS provide a valuable aid in tailoring interventions, optimizing resource allocation, and strategically placing healthcare facilities to address specific chronic health challenges in diverse geographical areas.

The combined analysis of different healthcare administrative datasets has proved useful to healthcare demand in diverse population segments (14). A similar approach was applied to ND using French national administrative databases (15). The prevalence of ND was presumed from drug reimbursement data, hospital stays or registration of a chronic condition, and the different neurological diseases were identified through validated algorithms (15). Here, we will apply a similar approach to estimate the prevalence and incidence of ND in the Marche Region.

The Marche Region is one of the Italian Regions where people live the longest lives, with a higher life expectancy at birth compared to the median one in Italy (81.2 vs. 80.5 years) (16) and a significant representation of older people among residents. Indeed, in the Marche Region, people aged ≥65 years represent over 25% of the total resident population, while in Italy people belonging to this age group are 24.1% of the total residents (16). Based on these epidemiological data, we would expect significant incidence and prevalence rates of ND in the Marche region. In order to make an estimate as precise as possible of ND burden on Marche Healthcare and families, we have drawn up the present study protocol, namely the TREND (Identifying aging TRajEctories toward chronic Neurodegenerative Diseases by means of Marche regional administrative databases) project.

The main aims of the TREND project are (i) to create a minimum dataset from administrative data of Marche residents; (ii) to estimate the prevalence and incidence of neurodegenerative diseases in the Marche Region, also by taking advantage of a GIS; (iii) to stratify the subjects into different risk groups that share common characteristics (demographic assessment, clinical status, comorbidity, drugs, and therapies); (iv) to assess the comorbidity index (CI) as a tool to depict the aging trajectories and discriminate between poor, medium and high risk of unsuccessful aging.

2 Methods and analysis

2.1 Study design

The TREND Project is a retrospective cross-sectional study. The source population includes permanent residents in the Marche region aged 40 years and older.

The dataset is built up by linking this database with the data on drug prescriptions, outpatient services, exemptions, and diagnosis for hospital discharge collected between 2014 and 2021. Three categories of subjects are identified, i.e., patients with (i) Parkinsonism that includes PD and Atypical Parkinsonism (AP), (ii) AD and non-AD dementia including PDD (subsequently referred to as 'Dementia'), and

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(iii) Parkinsonism and Dementia. To exclude the patients with prior ND diagnosis a 5-year period of freedom from disease is deemed as appropriate.

The three groups of patients are identified through validated algorithms analysis of administrative healthcare databases. Moreover, data on clinical outcomes (re-hospitalization, mortality, and comorbidities) and therapeutic approaches (drugs and medicines) are integrated with state-of-the-art statistical methods to define patients into different risk clusters and to measure a "chronicity index."

2.1.1 Data sources

Data sources include the administrative electronic health archives present in the Marche region in order to trace the subject in all accesses to the health services of interest for the period 2014–2021. Specifically:

- Patient registry: these inhabitants have been identified using the archives of the Regional Population Registry (ARCA) that contain demographic and administrative information. To preserve the individual's privacy, data are anonymized by removing personal information.
- Outpatient's drug prescription database reporting all dispensations of drugs reimbursable by the National Health System (NHS) and the list of drugs directly supplied by the hospital pharmacy.
- Hospital Discharge Records (HDR) considering the principal and up to five secondary diagnoses, categorized using the International Classification of Diseases-Ninth Revision, Clinical Modification code (ICD-9), and different precision levels were considered based on the disease.
- Ticket Exemptions, that record information on all co-payment exemptions due to chronic disease.

In addition to these fundamental databases, other linking tables are considered, i.e., the database containing detailed information on drugs (commercial name, ATC and AIC codes, public price, etc.), regional and municipal population (obtained from Istat source), and other data not directly used by the study protocol (e.g., hospital pharmaceuticals).

After matching patient data from various tables based on their social security number, the data was anonymized, assigning each patient a unique ID to ensure irreversibility and prevent any attempt to trace back to the social security number from the corresponding ID.

2.2 Data management and quality check

To improve the accuracy of the data in preparation for subsequent analyses, data from all sources have been cleaned, and prepared for analysis by the in-house statistics, bioinformatics and data management teams following main operating procedures:

- Administrative data coming from various tables with different structures and characteristics have been processed to harmonize their structure;
- Inconsistent or incorrect data have been assessed by logical and range checks to address ambiguous values (non-uniform coding, empty values, and missing data);
- The source data in a raw format (i.e., as a single text field in the case of exemptions) have been validated with a normalization procedure.

In addition to data management, a Structured Query Language (SQL) syntax is set up in order to perform quality check procedures.

For each available year, a record count is performed, together with the count of unique patients (distinct identification codes), and several reference fields (e.g., number of prescriptions for pharmaceuticals, number of diagnoses for hospitalizations, etc.). Moreover, missing and invalid values were handled (i.e., by replacing blank text fields, or inconsistent/dummy values). In order to assess the temporal trend of these differences, the overall average for all available years and the study horizon 2014–2021, and the percentage shares on the total number of records and on the total number of patients, are calculated for each table.

2.3 Algorithm for subject extraction

First, patients with PD and Dementia will be identified from administrative regional databases records, by filtering according to prescription data, hospital discharge records (HDRs), and medical exemptions due to chronic disease. Based on the Italian guidelines for the diagnosis and treatment of PD (17) and AD (18), tracer drugs for PD and Dementia are identified (Table 1). Specifically, pharmacological treatments for AD (reimbursed by the Italian National Healthcare System) include anticholinesterase drugs and memantine. Nevertheless, the rate of anticholinesterase drug prescription in AD is extremely variable, ranging from 11 to 80% in the geriatric population (19). Moreover, there are no specific drugs for non-AD dementia that are reimbursed by National Health system. Therefore, the estimation of Dementia incidence and prevalence based on specific AD pharmacological therapy prescription is clearly associated with a relevant risk of underestimation. Thus, we have considered the inclusion of further drug classes in the list of tracer active principles. According to extensive literature data, patients with dementia are significantly more likely to be prescribed antipsychotic and antidepressant drugs compared to subjects without dementia (20, 21). Moreover, a previous machine learning analysis of administrative data revealed that, besides anticholinesterase drugs, antipsychotics were the most important predictors of dementia (22). Thus, we included antipsychotic drugs and the antidepressant drugs trazodone and mirtazapine in the list of tracer drugs (Table 1). In this case, to avoid overestimation due to inappropriate inclusion of subjects suffering from primary psychiatric issues, we excluded subjects that were hospitalized for schizophrenia, bipolar disorder, or major depressive disorder or were attributed a ticket exemption for psychoses.

HDRs have been analyzed to extract subjects that had an in-hospital stay during the observation period for the diagnostic work-up and management of PD and dementias. The list of ICD-9 codes selected for the disease tracing has been drawn up to be as comprehensive as possible, following the different interpretations of the guidelines for compiling the HDRs adopted by the hospitals operating in the area. For example, although the indication to report the ICD-9 diagnosis code as specifically as possible (e.g., 290.0) is in force, in many cases the HDR is filled with the parent code of the

TABLE 1 ATC codes for tracer drugs.

Neurodegenerative disease	ATC code of tracer drugs
Dementia	N06DA02 Donepezil
	N06DA03 Rivastigmine
	N06DA04 Galantamine
	N06DX01 Memantine
	N05AA01 Chlorpromazine
	N05AA02 Levomepromazine
	N05AA03 Promazine
	N05AD01 Haloperidol
	N05AH03 Olanzapine
	N05AH04 Quetiapine
	N05AL05 Amisulpride
	N05AX08 Risperidone
	N05AX09 Clotiapine
	N05AX12 Aripiprazole
	N06AX05 Trazodone
	N06AX11 Mirtazapine
Parkinsonism	N04BA02 Benserazide/levodopa
	N04BA03 Carbidopa/levodopa/entacapone
	N04BA05 Melevodopa/carbidopa
	N04BA06 Melevodopa/carbidopa
	R05DB27 Levodropropizine
	N04BC04 Ropinirole
	N04BC05 Pramipexole
	N04BC07 Apomorphine
	N04BC09 Rotigotine
	N04BD01 Selegiline
	N04BD02 Rasagiline
	N04BD03 Safinamide
	N04BX01 Tolcapone
	N04BX02 Entacapone
	N04BX04 Opicapone

TABLE 2 ICD-9 codes for the identification of subjects with dementia.

Neurodegenerative disease	ICD-9 codes
AD	331.0 –Alzheimer's disease
Non-AD dementia	290 – Dementias 290.0 – Uncomplicated senile dementia 290.1 – Pre-senile dementia 290.10 – Uncomplicated pre-senile dementia 290.11 – Pre-senile dementia with delirium 290.12 – Pre-senile dementia with delusional aspects 290.13 – Pre-senile dementia with depression aspects 290.2 – Senile dementia with delusional or depression aspects 290.20 – Senile dementia with delusional aspects 290.21 – Senile dementia with depression aspects 290.3 – Senile dementia with delirium 290.4 – Vascular dementia 290.40 – Uncomplicated vascular dementia 290.41 – Vascular dementia with delirium 290.42 – Vascular dementia with delusions 290.43 – Vascular dementia with behavioral disturbance *294.1 – Dementia in other diseases classified elsewhere** *294.10 – Dementia in other diseases classified elsewhere, without behavioral disturbances** *294.11 – Dementia in other diseases classified elsewhere, with behavioral disturbances** 331.1 – Frontotemporal dementia 331.11 – Pick's disease 331.19 – Other frontotemporal dementias 331.2 – Senile degeneration of brain 331.3 – Communicating hydrocephalus 331.5 – Normal pressure hydrocephalus 331.7 – Degeneration of brain in other diseases classified elsewhere 331.82 – Dementia with Lewy bodies 331.9 – Brain degeneration, unspecified

*Patients with either of the codes 294.1, 294.10, or 294.11 should not be included in the non-AD group if they also have the code 331.0 (Alzheimer's disease) among the diagnoses. Conversely, if one or more of these codes are not associated with the 331.0 code, the patient should be included in the non-AD group.

diagnosis tree (e.g., 290). The tracer ICD-9 codes for each group are listed in Table 2.

To identify subjects with neurodegenerative disease based on prescription charge exemption due to chronic disease (Exemptions), the codes in Table 3 are applied.

After the identification and extraction of subjects according to ATC/ICD-9/exemption tracer codes, we have proceeded as follows to estimate the prevalence of subjects in each group. First, occasional PD and Dementia drug users, defined as subjects receiving a single prescription of a tracer drug during the observation period, are identified, and removed. In identifying cases of PD, the use of ICD-9 codes listed in HDRs poses some limitations as they often fail to distinguish among Parkinson's disease, atypical parkinsonism, and tremor syndromes (23). Therefore, PD patients (Group 1) are identified according to the criterion of either the non-occasional use of PD tracer drugs (listed in Table 1) or the presence of the exemption code '038'. According to this definition, patients with early-stage disease may be undetectable. Then, we proceeded by identifying patients with Dementia (Group 2), based on the possession of at least one of the following requirements: (i) non-occasional presence of ATC tracing codes for AD or non-AD dementia (Table 1); (ii) specific diagnosis reported in HDR of either AD (as a primary and secondary diagnosis) or any other form of dementia (Table 2); (iii) attribution of one of the exemption codes listed in Table 3 for dementia; (iv) in presence of non-occasional consumption of antipsychotic drugs, trazodone and/or mirtazapine as the only fulfilled criterion, absence of hospitalization for schizophrenia (ICD-9 code 295.xx), bipolar disorder (296.0x, 296.1x, 296.4x–296.9x), or major depressive disorder (296.2x, 296.3x, 311.xx), and absence of the exemption code '044,' which identifies psychoses. The following step consists in the adjudication of retrieved subjects into the dementia group based on the scheme reported in Figure 1.

TABLE 3 Exemption codes.

Neurodegenerative disease	Exemption codes
PD	038 – Parkinson's disease and other extrapyramidal diseases
AD	029 – Alzheimer's disease
Non-AD dementia	011 – Dementia, all subcodes except 011.291.1 (alcohol amnesic syndrome) and 011.294.0 (nonalcoholic amnesic syndrome)

In order to operationalize the algorithm above (described in Figure 1), an SQL procedure is performed, involving a series of steps for data extraction, linkage, and analysis:

(i) Identification of tracking drugs according to the ATC codes listed in the protocol and matching them with the AIC codes present in the pharmaceutical flows through the linking database;
(ii) Extraction from the pharmaceutical flows of the records corresponding to the tracer drugs and the selected exemption codes;
(iii) Identification of subjects with selected exemption from the exemption database;
(iv) Integration of the inclusion criteria on HDR diagnoses (for the dementia group only);
(v) Identification of diagnoses and extraction of the corresponding subjects;
(vi) Construction of an analytic database per patient (where each record corresponded to a unique anonymous ID), containing the selection criteria and group classification;
(vii) Creation of a demographic database according to the project requirements (age, sex, mortality, and residential area). Association (linkage) of the medical record to patients according to the anonymous identifiers.
(viii) Construction of automated count tables for each of the groups and subgroups.
(ix) Construction of algorithms for automated calculation of prevalence and incidence (comprehensive at regional aggregate level) for the three groups.

2.4 Data visualization platform and GIS

The data visualization tool will consist of a web interface, divided into two areas. The first one is for configuring the filters (Figure 2A), and the second one is for presenting the output data (Figure 2B). In addition, we have developed a geographical information system (GIS) to support the regional health policy and to present how the epidemiological measures can be visualized by users, either professionals, politicians or citizens, in an easy and effective way.

In order to better understand how the platform works, a description of the filters is provided below.

- Indicator. The first filter is called "indicator" and refers to which indicator we are interested in visualizing. The available indicators are incidence, prevalence (global, sex-specific, for subjects aged >65 and >75 years), gross expense (total, per patient, pro-capita), hospitalizations (total, per patient, pro-capita), mortality rate, prescriptions (total and pro-capita);
- Patient cohort. The patient cohort filter allows to choose for which cohort of patients we want to visualize data: patients with PD or dementia;
- Local Level. The local level indicates at which level the data should be aggregated. In the TREND database, data are stored at the municipality level, but users may consider as much relevant to explore data aggregated at the province or regional level;
- Year. This filter allows setting the year we are interested in visualizing data for.

As described above, the remaining area is dedicated to data visualization, which can be done in two different modalities according to which level of data aggregation has been selected at the filter "Local level":

- For "municipality" and "province" levels, the data will be represented, for a specific year, in the form of a map in which each area is colored with a different shade of color depending on the percentile of the selected indicator;
- For the "region" level, the data will be presented in a table in which each row will report the corresponding data of a specific year.

2.5 Assessment of comorbidities

To identify clusters of comorbidities in patients with ND, the Comorbidity Index (CI) is computed for each patient with Parkinsonism or Dementia. The presence of the comorbidities included in the CI is inferred based on hospital discharge records and ticket exemptions due to chronic disease. We have calculated the Charlson Comorbidity Index (CCI) for medical conditions by the ICD-9 retrieved from the publication of Glasheen et al. (24). Table 4 lists the CCI comorbidities, the tracer ICD-9, and exemptions codes. Patients will be categorized into low risk (no comorbidities), intermediate risk (1 comorbidity), and high risk (2+ comorbidities).

2.6 Statistical analysis

After extracting patients affected by Parkinsonism and Dementia over the period 2014–2021, all entries retrieved in each year of the observation period will be used for calculating prevalence and incidence rates for each year. The incident cohort represents the proportion of individuals in which the neurodegenerative pathology has manifested during the inclusion period. Subjects are identified through their presence in at least one of the archives considered in the recruitment year and the simultaneous absence in all the archives of interest in the 5 years preceding the one under consideration. Each subject will be identified by its own unique anonymous code across all data sources.

A descriptive analysis of the patients will be conducted using uni- and bi-variate statistical analyses, with the aim of verifying the comparability of different risk groups for ND that share common characteristics (demographic assessment, clinical status, drugs, and therapies). Continuous variables will be expressed using means with standard deviations (SD) and medians with

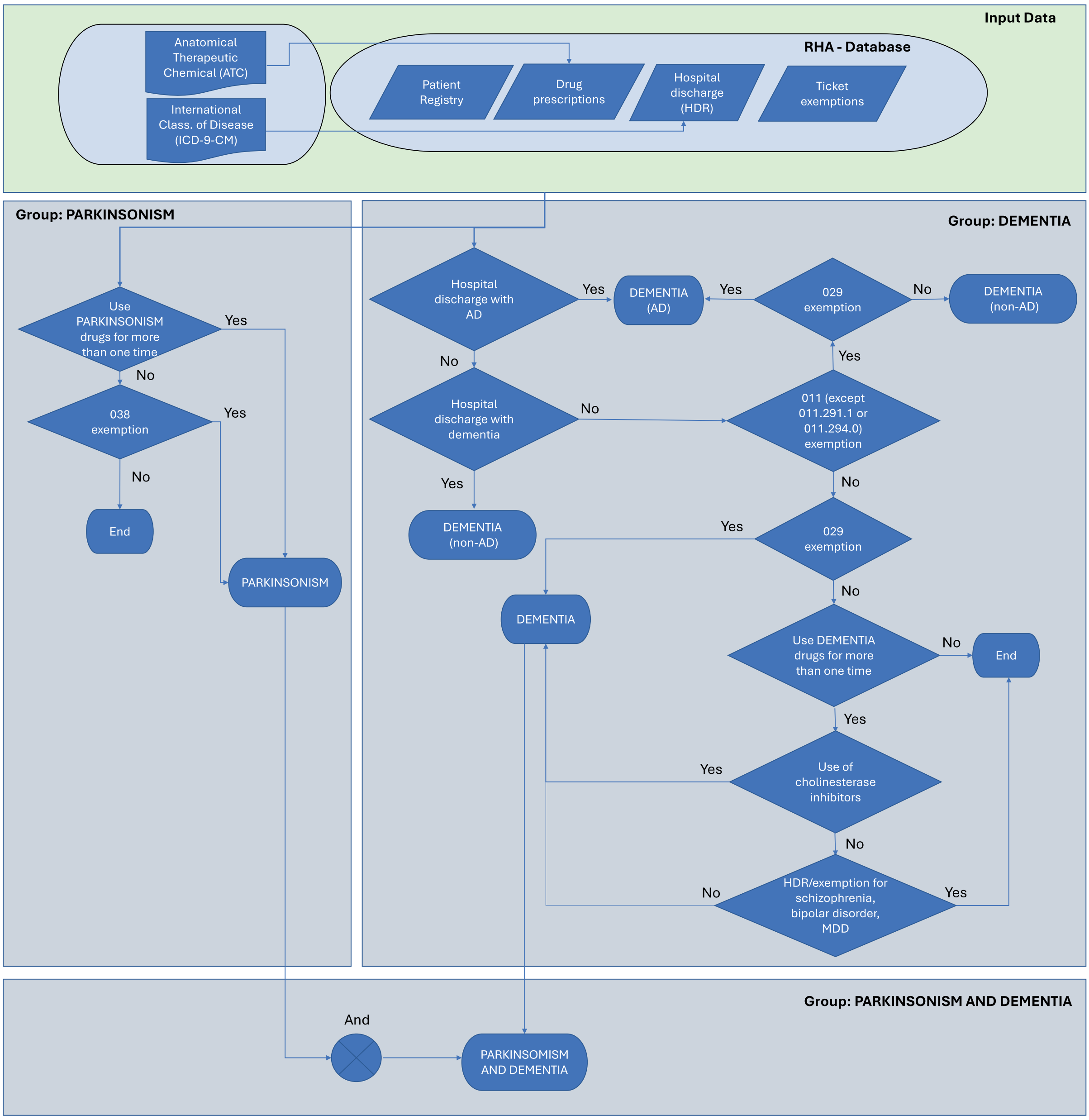

FIGURE 1
Flow diagram for the adjudication of cases into the Parkinson's and Dementia groups. HDR, hospital discharge record.

ranges. For variables with a normal distribution, statistical comparisons among groups will be made using an analysis of variance test. Measurements with discrete distribution will be expressed as percentages (%) and analyzed by the Chi-squared or Fisher's exact test when appropriate.

Cluster analysis will be applied to stratify patients affected by ND into different risk groups of "unsuccessful aging." Discriminant function analysis will be performed using both forward and backward stepwise algorithms on each cluster model to evaluate the input variables that will be significant determinants of model structure, using the hierarchical clustering approach. The complete linkage criterion will be used to measure the distances between clusters because it leads to the best result. An advantage of hierarchical clustering on variables is that the outcome can easily be represented by means of a dendrogram. The groups will be identified based on the following dimensions: age, gender, ND, comorbidities, medications, and rehospitalization.

The distribution of the CI in patient cohorts will be evaluated according to year, sex, and age classes.

The aging trajectories will be reconstructed by applying a regression model to depict the age-related trend of the risk profiles of patients. The regression model will include variables or sets of variables forced into the equation at each step and only the final models will be presented with all variables entered simultaneously.

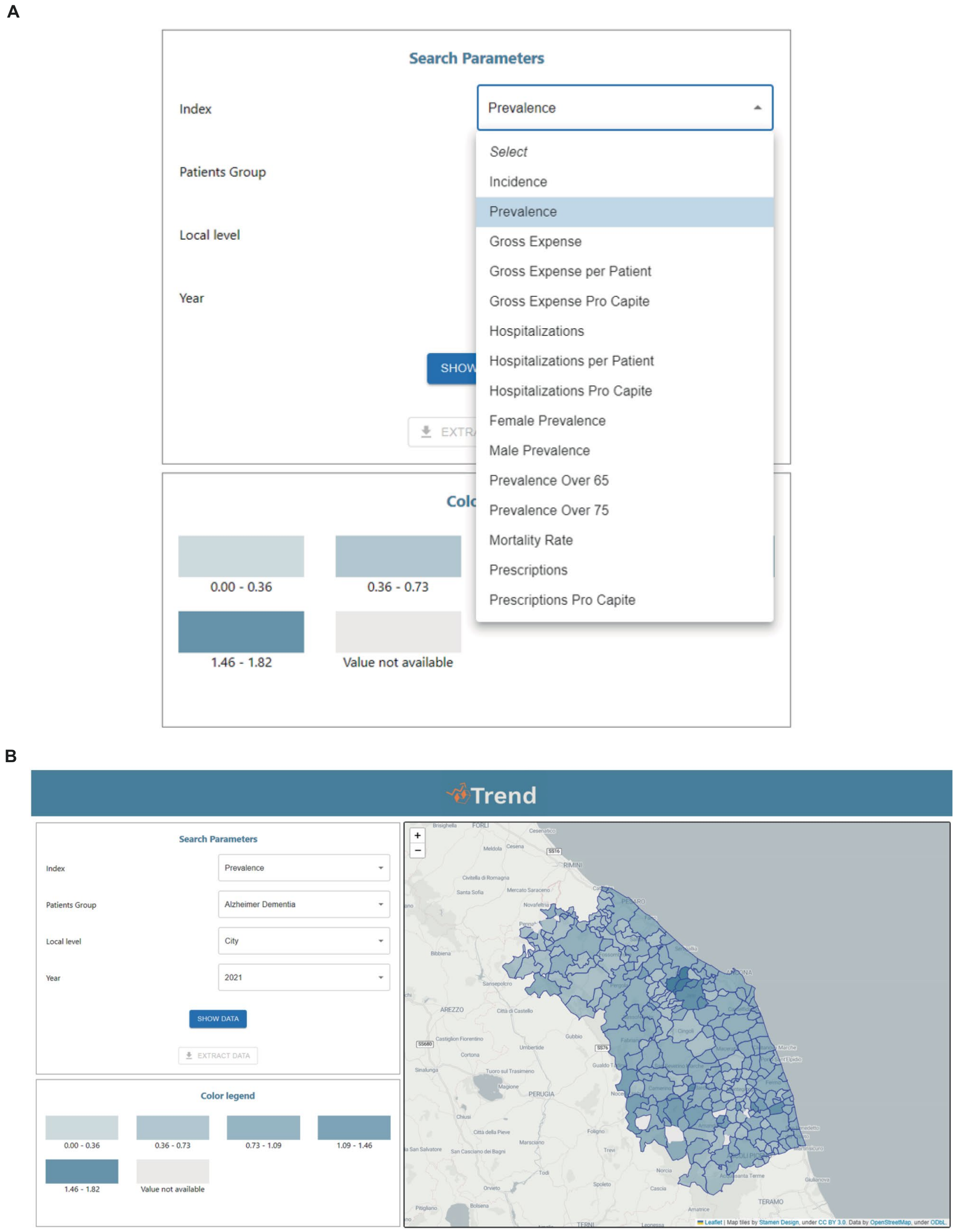

FIGURE 2
Representative screenshots of the Geographical Information System (GIS) user interface. **(A)** Search parameters, with the index selection tool expanded, **(B)** output of the prevalence of Dementia in 2021 grouped at the municipality level.

Logistic and survival regression analysis will be applied to calculate the risk of death, hospitalization, and onset of other diseases considering the following covariates: age, sex, groups of pathologies (Dementia vs. PD), number of medications taken, types of medications, frequency and duration of re-hospitalizations and CI. Aging trajectories will be constructed by analyzing the estimated values from logistic and survival regression analyses with patients' ages based on risk and disease clusters (Dementia vs. PD).

TABLE 4 Tracer exemption and hospital discharge record (HDR) ICD-9 for each medical condition included in the Charlson Comorbidity Index (CCI).

		CCI points	Exemption code	HDR ICD-9
1	Myocardial infarction	1	–	410, 412
2	Congestive heart failure	1	021	398.91, 402.01, 402.11, 402.91, 404.01, 404.03, 404.11, 404.13, 404.91, 404.93, 425.4, 425.5, 425.6, 425.7, 425.8, 425.9, 428.
3	Peripheral vascular disease	1	0C02	093.0, 437.3, 440, 441, 443.1, 443.2, 443.8, 443.9, 447.1, 557.1, 557.9, V43.4
4	Cerebrovascular disease	1	0B02	362.34, 430, 431, 432, 433, 434, 435, 436, 437, 438
5	Dementia	1	011	290, 290.1, 290.2, 290.3, 290.4, 294, 294.1, 294.2, 294.8, 331, 331.1, 331.2, 331.7, 797
6	Chronic pulmonary disease	1	024 or 057	490, 491, 492, 493, 494, 495, 496, 500, 501, 502, 503, 504, 505, 506.4, 508.1, 508.8
7	Rheumatic disease	1	006 or 067	446.5, 710, 710.1, 710.2, 710.3, 710.4, 714, 714.1, 714.2, 714.8, 725
8	Peptic ulcer disease	1	-	531, 532, 533, 534
9	Hemiplegia or paraplegia	2	-	334.1, 342, 343, 344
10	Renal disease	2	023	403.01, 403.11, 403.91, 404.02, 404.03, 404.12, 404.13, 404.92, 404.93, 582, 583, 583.1, 583.2, 583.3, 583.4, 583.5, 583.6, 583.7, 585, 586, 588, V42.0, V45.1, V56
11	Liver disease, mild	1	016	070.22, 070.23, 070.32, 070.33, 070.44, 070.54, 070.6, 070.9, 570, 571, 573.3, 573.4, 573.8, 573.9, V42.7
	Liver disease, moderate to severe	3	008	456, 456.1, 456.2, 572.2, 572.3, 572.4, 572.8
12	Diabetes without chronic complications	1	013	250.8, 250.9, 249, 249.1, 249.2, 249.3, 249.9
	Diabetes with chronic complications	2	013	250.4, 250.5, 250.6, 250.7
13	Any malignancy	2	048	14x., 15x., 16x., 170, 171, 172, 174, 175
	Metastatic solid tumor	6	048	196, 197, 198, 199
14	HIV infection, no AIDS	2	020	042
	AIDS	6	020	112, 180, 114, 117.5, 007.4, 078.5, 348.3, 054, 115, 007.2, 176, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 031, 136.3, V12.61, 046.3, 003.1, 130, 799.4, 010, 011, 012, 013, 014, 015, 016, 017, 018

Performances of model approaches will be tested with simulated scenarios and real-world data using the risk stratification cohorts of the present study. Simulations will be generated under a number of scenarios accounting for different patterns of aging of different risk groups of neurodegenerative diseases.

STATA ver.18 (StataCorp, College Station, TX, USA) and R version 4.2.2 (R Core Team) software will be used to perform data analyses.

3 Discussion

Dementia is one of the major health challenges for our generation, with close to 50 million people affected worldwide. Dementia is currently the seventh leading cause of death and one of the major causes of disability and dependency among older people globally so that the personal, social, and economic consequences of dementia are enormous. In recent years, healthcare research in planning care strategies for dementia has received increasing attention (25). Healthcare administrative databases are increasingly employed to improve care transitions between different settings (Family Medicine Groups, home care, and community services) and the care of people living with dementia and their caregivers (26). Efforts are needed to monitor the incidence and progression of neurodegenerative diseases also in our Country, and Italian administrative databases offer an opportunity for the innovative generation of information. Indeed, archives of the National Health Service that provide demographic and administrative information can be linked with archives of ticket exemptions, hospital discharge, and drug prescriptions to estimate the prevalence of subjects affected by specific conditions and to stratify the population according to such conditions (27, 28).

Attention to local and regional needs for neurodegenerative diseases is crucial for organizing services in the framework of National Laws and assuring basic levels of quality care (LEA). Our research may contribute to reaching these goals through the integration of existing administrative databases on ND in order to create a Marche Regional ND dataset, that could be implemented at the National level. The identification of subjects affected by a specific disease through access to healthcare services starting from drug prescription data registered in an administrative healthcare archive has the advantage of using codified, standardized, and quality-controlled definitions. It also represents a point in the natural history of the disease that is easily identifiable and applicable to all the individuals considered, easily and homogeneously identifying the onset of the disease. Despite minimal regional variations in the process of data collecting, our protocol is feasible for the immediate application also in other Italian regions. Indeed, computer-based gathering of hospital discharge records and drug reimbursement data is in force in all the Italian regions, and the exemption codes that were considered in the present protocol are applicable throughout the entire National healthcare system. Despite the peculiarities of the Italian healthcare system, it remains evident that studying algorithms proposed internationally also provides valuable insights into the selection of criteria, especially concerning medication criteria and diagnostic codes for hospital stays. The methodology presented in this protocol may be easily adapted to other countries, including healthcare systems based on insurance, as universal ICD-9 and ATC codes are utilized for retrieving cases, which are commonly available across various healthcare systems. The possible underestimation of the individuals number affected by the pathological condition of interest (limited sensitivity) is compensated by identified patients who reasonably present the pathological condition of interest (good specificity), being negligible the probability that a subject not affected by the pathology will access specific health services.

Existing administrative databases are readily available and cost-effective and allow for the analysis of large population samples, providing statistical power to detect trends and patterns in ND incidence and prevalence. Possible limitations of this approach may include selection bias, misclassification errors inherent in retrospective data collection, limited completeness of administrative data, which may vary across different healthcare settings, and the inability to capture detailed clinical information that may be available in prospective registries that may, on turn, suffer from recruitment bias and required challenging and time-consuming follow-up procedures (29).

Overall, based on the data collected in Marche regional healthcare administrative databases on PD and dementia, it will be possible to calculate the prevalence rates for each year, reconstruct the aging trajectories, depict the age-related trends of the risk profiles of patients, and provide geographical information on ND patients in Marche region. The results of this project will support regional health policy planning and contribute to the successful implementation of integrated care for patients affected by ND at the regional and national levels.

Ethics statement

As required by the Ministry of Health, this retrospective study was notified to the Marche Region Ethics Committee. Written informed consent to participate in this study was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and the institutional requirements.

Author contributions

LS: Conceptualization, Data curation, Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. JS: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. LB: Methodology, Validation, Writing – review & editing. FB: Data curation, Formal analysis, Software, Writing – review & editing. ML: Formal analysis, Software, Writing – review & editing. DR: Methodology, Writing – review & editing. AG: Validation, Writing – review & editing. LP: Investigation, Software, Visualization, Writing – review & editing. GR: Resources, Supervision, Writing – review & editing. MP: Data curation, Resources, Writing – review & editing. GP: Methodology, Writing – review & editing. RR: Resources, Writing – review & editing. FO: Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

FB and LP were employed by the company Tech4Care srl.

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Frailty and poor physical functioning as risk factors for driving cessation

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Introduction: Frailty and low physical performance are modifiable factors and, therefore, targets for interventions aimed at delaying driving cessation (DC). The objective was to determine the impact of frailty and physical performance on DC.

Methods: Multisite prospective cohort of older drivers. The key inclusion criteria are as follows: active driver age 65–79 years, possessing a valid driver's license, without significant cognitive impairment, and driving a 1996 car or a newer model car. Of the 2,990 enrolled participants, 2,986 (99.9%) had at least one frailty or Short Physical Performance Battery (SPPB) measure and were included in this study. In total, 42% of participants were aged 65–69 years, 86% were non-Hispanic white, 53% were female, 63% were married, and 41% had a high degree of education. The Fried Frailty Phenotype and the Expanded Short Physical Performance Battery (SPPB) from the National Health and Aging Trends Study were utilized. At each annual visit, DC was assessed by the participant notifying the study team or self-reporting after no driving activity for at least 30 days, verified via GPS. Cox proportional hazard models, including time-varying covariates, were used to examine the impact of the SPPB and frailty scores on time to DC. This assessment included examining interactions by sex.

Results: Seventy-three participants (2.4%) stopped driving by the end of year 5. Among women with a fair SPPB score, the adjusted hazard ratio (HR) of DC was 0.26 (95% confidence interval (CI) 0.10–0.65) compared to those with a poor SPPB score. For those with a good SPPB score, the adjusted HR of DC had a *p*-value of <0.001. Among men with a fair SPPB score, the adjusted hazard ratio (HR) of DC was 0.45 (95% CI 0.25–0.81) compared to those with a poor SPPB score. For men with a good SPPB score, the adjusted HR of DC was 0.19 (95% CI 0.10–0.36). Sex was not an effect modifier between frailty and DC. For those who were categorized into pre-frail or frail, the adjusted ratio of HR to DC was 6.1 (95% CI 2.7–13.8) compared to those who were not frail.

Conclusion and relevance: Frailty and poor physical functioning are major risk factors for driving cessation. Staying physically active may help older adults to extend their driving life expectancy and mobility.

KEYWORDS
older adults, driving cessation, frailty, physical performance, driving outcomes

Introduction

Driving cessation (DC) decreases independence and leads to poorer physical, mental, and social health (1). Frailty and physical performance are both modifiable factors by behavioral factors such as progressive exercise interventions (2). The Short Physical Performance Battery (SPPB), a comprehensive lower extremity physical performance measure is a strong predictor of skilled nursing admission, morbidity, and mortality (3, 4). It has also been found to be a good measure of physical functioning and driving outcomes (3, 4). The SPPB has previously been assessed as a predictor of DC (4). Gill et al. found that low SPPB scores were associated with 120% of the hazard of DC [HR = 2.2, 95% CI 1.3, 3.7] compared to high scores (3, 5). However, this sample came from one health plan in one geographic region and was oversampled based on physical disability (5). The data from our study sample may yield results that are more generalizable than those from the study by Gill et al. (5).

While the SPPB provides a valuable measure of physical capabilities in terms of lower extremity physical function, frailty is a clinical syndrome that develops following a decline in function and resilience across numerous physiological systems. Therefore, frailty provides an alternative, more comprehensive measure of physical capabilities than the SPPB (6, 7). Frailty is associated with falls, disability, hospitalization, and injury mortality (6–8). Baseline frailty in this cohort has previously been found to be associated with the rate of DC at 1 year HR of 4.2 (95% CI: 1.9–9.1) for pre-frail and HR of 6.1 (95% CI: 1.4–27.3) for frail participants (8). Ishii et al. evaluated driving cessation as the exposure and physical frailty transition as the outcome in a cohort of 2,934 older Japanese adults (9). They reported that driving cessation was a risk factor for frailty, as indicated by a 4.6% versus 17.1% difference in the rates for frailty transition (9). Our study is the first to evaluate time-varying frailty as the exposure and driving cessation as the outcome longitudinally.

The aim of this study was to examine the impact of frailty and SPPB on the likelihood of DC. We hypothesized that the presence of frailty and poor SPPB would lead to a higher likelihood of DC.

Methods

Participants, design, and procedures

We utilized the AAA Longitudinal Research on Aging Drivers (LongROAD) cohort, and the methods were described in detail previously (10). Using a clinical convenience sample, 40,806 patients were approached, with 7.3% enrolling in the study. LongROAD was a multisite prospective cohort of 2,990 older drivers enrolling participants aged 65–79 years recruited between July 2015 and March 2017 from five sites: Ann Arbor, MI; Baltimore, MD; Cooperstown, NY; Denver, CO; and San Diego, *CA*. The inclusion criteria were as follows: (1) living at their current address 80% of the year, (2) possessing a valid driver's license, (3) driving on average at least once per week, (4) having no significant cognitive impairment, (5) driving one vehicle ≥80% of the time, (6) driving a vehicle with model year 1996 or newer with an available OBDII port, (7) not involved in another driving study, (8) planning to stay in their current location for another 5 years, and (9) not living with a current LongROAD participant (10). The annual data collection was completed in the following date ranges: Baseline —6 July 2015 to 31 March 2017; Year 1—6 July 2016 to 20 June 2018; Year 2—21 June 2017 to 8 June 2019; Year 3—3 July 2018 to 30 April 2020; Year 4—25 June to 24 November 2021; and Year 5—31 August 2020 to 27 September 2022. The Baseline, Year 2, and Year 4 or 5 (due to COVID-19 half of the cohort in Year 4 and the other half of the cohort in Year 5) visits were conducted in person. The other visits were conducted by telephone. Participants classified by the Fried Frailty Phenotype (FFP) or SPPB at least once ($n = 2,986$, 99.9%) were included in this analysis.

Measures

Covariates

It is well known that poor cognition and vision are important risk factors for driving cessation. Episodic and working memory were measured with immediate and delayed word recall tasks with higher scores indicative of better cognitive health (11). The Motor Free Visual Perception Test (MVPT-3) measured overall visual perception ability based on test items 22–34 (scores ranged from 0 to 13 with 13 indicating better visual perception) (12, 13).

Exposure

Short physical performance battery

Lower extremity physical function was measured using scores from the timed components of the National Health and Aging Trends Study (NHATS) Expanded SPPB: walking speed; repeated chair stands; three original standing balance tests (side-by-side, semi-tandem, and tandem); and an additional balance test (standing on one leg with eyes open) (14). Each participant received scores ranging from 0 to 4 for the three components. An SPPB summary score ranging from 0 to 12, with 12 representing the highest performance level, was created by summing the three scores. To account for a high level of performance in this cohort, cutoffs for each category were raised so that the SPPB scores are categorized as poor (0–7), fair (8–10), and good (11–12) (3).

Frailty

Frailty was measured using the FFP (6–8). Frailty status was evaluated by assessing five criteria on a pass/fail basis: shrinking (unintentional loss of ≥10 pounds in the past year or being underweight according to a body mass index (BMI) of ≤18.5 kg/m^2), weakness (grip strength in the lowest 20% of the population, adjusted for sex and BMI), exhaustion (self-report of having poor endurance and energy), slowness (slowest 20% of the population

TABLE 1 Characteristics of baseline participants ($N = 2,986$).

Variables	N	%	Mean (SD)
Age (years)			
65–69	1,242	41.6%	
70–74	1,036	34.7%	
75–79	708	23.7%	
Sex			
Male	1,403	47.0%	
Female	1,583	53.0%	
Race/ethnicity			
White, non-hispanic	2,555	85.9%	
Black, non-hispanic	213	7.2%	
Other	206	6.9%	
Marital status			
Married	1873	63.3%	
Not married	1,085	36.7%	
Education			
High school or less	336	11.3%	
Associate's degree	724	24.3%	
Bachelor's degree	696	23.4%	
Advanced degree	1,221	41.0%	
SPPB			
0–7 (poor)	572	19.4%	
8–10 (fair)	1,350	45.8%	
11–12 (good)	1,025	34.8%	
Frailty			
Not frail	1,222	41.2%	
Pre-frail or frail	1742	58.8%	
Motor free visual perception test (1–13 higher better)			11.5 (1.7)
Immediate and delayed correct word recall			10.5 (3.0)

based on time to walk 15 ft., adjusted for sex, and standing height), and low physical activity (not having recently walked for exercise or engaged in vigorous physical activity). If three or more of these criteria were met, the participant was classified as frail; if one or two criteria were met, the participant was classified as pre-frail; and if none was met, the participant was classified as not frail (6). In this study, the pre-frail and frail categories were collapsed into the "frail" category due to the models not converging with separate categories.

Primary outcomes

Driving cessation

Driving cessation was based on participants' self-report, which was captured in one of the three ways. First, questions about driving status were assessed at each annual follow-up visit. Second, participants were instructed to notify the study team if they stopped driving. Third, participants' driving activity was monitored using an in-vehicle GPS device. If there was no driving for at least 30 days, the study team reached out to participants to identify their current driving status.

Statistical analysis

Cox proportional hazard (PH) models with time-varying covariates were used to examine the impact of annual SPPB and frailty with time to DC among those who were still driving. SPPB and frailty were examined in separate PH models. The model fits data from day 0 to the end of the follow-up for each person. Each model included the following covariates to control confounding of data: age, sex, marital status, education, delayed and immediate word recall, and MVPT-3. All these covariates (except for sex) were time-varying (The model estimates were adjusted for clustering within each site.). The models were tested for interaction by sex.

Results

At baseline, 42% were 65–69 years old, 53% were female, 86% were non-Hispanic white, 41% had an advanced degree, and 63% were married (Table 1).

Seventy-three participants stopped driving by Year 5. One participant resumed driving after having stopped. The interaction between SPPB fair level and sex was not significant ($p = 0.32$), and the

TABLE 2 Unadjusted and adjusted association of short physical performance battery (SPPB) with time to driving cessation.

	Unadjusted hazard ratio (95% confidence interval)[1]	Adjusted hazard ratio (95% confidence interval)[2]
SPPB status		
Poor	Ref	Ref
Fair	0.29 (0.19–0.46)	0.31 (0.18–0.52)
Good	0.08 (0.05–0.14)	0.09 (0.04–0.20)
Male individuals	**Unadjusted hazard ratio (95% confidence interval)[3]**	**Adjusted hazard ratio (95% confidence interval)[4]**
SPPB status		
Poor	Ref	Ref
Fair	0.33 (0.14–0.80)	0.45 (0.25–0.81)
Good	0.08 (0.05–0.13)	0.19 (0.10–0.36)
Female individuals	**Unadjusted hazard ratio (95% confidence interval)[5]**	**Adjusted hazard ratio (95% confidence interval)[4]**
SPPB status		
Poor	Ref	Ref
Fair	0.28 (0.15–0.52)	0.26 (0.10–0.65)
Good	0.12 (0.04–0.35)	4.0×10^{-8} ($1.5 \times 10^{-8} - 1.1 \times 10^{-7}$)

[1]Total $N = 2,976$. [2]Adjusted for age, sex, marital status, education, delayed and immediate word recall, vision, and adjusting for clustering within each site. [3]Total $N = 1,358$. [4]Adjusted for age, marital status, education, delayed and immediate word recall, vision, and adjusting for clustering within each site. [5]Total $N = 1578$.

TABLE 3 Unadjusted and adjusted association of frailty status with time to driving cessation.

	Unadjusted hazard ratio (95% confidence interval)[a]	Adjusted hazard ratio (95% confidence interval)[b]
Frailty Status		
Not Frail	Ref	Ref
Pre-frail and Frail	2.69 (1.73–4.16)	6.12 (2.72–13.78)

[a]Total $N = 2978$.
[b]Adjusted for age, gender, marital status, education, delayed and immediate word recall, and vision, and adjusting for clustering within each site.

interaction between SPPB good level and sex was significant ($p = 0.0001$). Overall, the interaction between SPPB and sex was significant ($p = 0.0271$), thus we ran both combined and stratified models by sex. For the combined models, after controlling for the time-varying covariates and comparing fair SPPB to poor SPPB, the results were as follows: adjusted (age, sex, marital status, education. delayed and immediate word (NOTE: NOT WORK), and vision) and adjusting for clustering within each site, the hazard ratio (aHR) was 0.31 (95% confidence interval (CI) 0.18, 0.52). Comparing good SPPB to poor SPPB the aHR was 0.09 (95% CI 0.04, 0.20). Among men, after controlling for the time-varying covariates (age, marital status, education, delayed and immediate word recall, and vision) and sex and adjusting for clustering within each site, the comparison of fair SPPB to poor SPPB, yielded the following results: the adjusted hazard ratio (aHR) was 0.45 (95% confidence interval (CI) 0.25, 0.81). Comparing good SPPB to poor SPPB, the aHR was 0.19 (95% CI 0.10, 0.36). Among women, after controlling for the time-varying covariates (age, marital status, education, delayed and immediate work recall, and vision) and adjusting for clustering within each site, comparing fair SPPB to poor SPPB, the results were as follows: adjusted hazard ratio (aHR) was 0.26 (95% CI 0.10, 0.65). Comparing good SPPB to poor SPPB, the aHR was <0.001 (see Table 2).

For FFP, sex was not a significant effect modifier in the relationship between frailty and driving cessation ($p = 0.9810$) (see Table 3).

After controlling for the time-varying covariates (age, marital status, education, delayed and immediate work recall, and vision) and sex and adjusting for clustering within each site, the comparison of pre-frail and frail individuals with those not frail resulted in a HR of 6.1 (95% CI 2.7, 13.8).

Discussion

This study assessed the impact of repeated measures of frailty and SPPB and followed participants over 5 years for the likelihood of DC. Over the 5-year study period, we found a protective association of higher physical performance, especially in women, and a negative association of frailty with time to DC. Ishii et al. found that DC was an independent risk factor of physical frailty transition in older adults, but this is the first study to assess the impact of physical frailty transition on DC (9). Previous research utilized the baseline LongROAD data and evaluated SPPB with driving space and crashes, but did not find effect modification by sex (3). Gill et al. (5) assessed the risk factors associated with long-term disability in the community including driving a car and found that women had a HR of 1.86 (95% CI 1.41–2.46). Although sex differences in frailty are widely reported, we did not find sex differences while evaluating the time to driving cessation (15–17). It has been reported that women are more likely to transition into frailty and are more likely to change frailty status, and this should be evaluated in future studies (15, 18).

Frailty is not a static state and has been shown to be a dynamic state in a meta-analysis of 42,775 community-dwelling older adults, where 13.7% of them improved (15, 18). Targeted exercise interventions starting with balance and flexibility and then progressing to endurance and resistance training are shown to improve physical function in frail older adults when targeting the pre-frail (2, 15). More specifically, the American College of Sports Medicine guidelines suggest that resistance and balance training begin before endurance training (2, 19). Interventions incorporating exercise, nutrition, cognitive training, and behavioral therapy have shown sustained (6 months) improvements in frailty status (2, 20). Physical activity interventions prevented decline in on-road driving performance (21, 22). Age-related changes in both physical and cognitive function lead to driving cessation. These non-cognitive changes such as muscle strength are modifiable (23).

A limitation of this study is the low response rate to our clinical convenience sample, which may limit the generalizability of the findings to the entire US population of older drivers (3, 10). In the methods paper for LongROAD, Li et al. stated that the sample was overrepresented by non-Hispanic whites and individuals with higher education status (3, 10). In summary, improving both frailty and physical performance in older adults by keeping physically active, ensuring adequate nutrition, and undergoing cognitive training are interventions that older adults can focus on to potentially delay DC.

Conclusion

Frailty and poor physical functioning impacted driving cessation. Future interventions should target frailty and poor physical functioning to prolong driving cessation.

Data availability statement

The datasets presented in this article are not readily available because data access limited due to constraints from the consent form. Requests to access the datasets should be directed to tjm2141@cumc.columbia.edu.

Ethics statement

The studies involving humans were approved by the institutional review boards of all participating institutions. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research on the health status and influencing factors of the older adult floating population in Shanghai

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Introduction: Over the past decade, against the dual background of population aging and mobility, the older adult/adults floating population has become a new type of mobile group in China, continually congregating in large cities, posing significant challenges to the socio-economic development, eldercare services, and public management of these metropolises. Shanghai, as a mega-city and the economic center of the China, is typically representative of the national population.

Methods: Based on the dynamic monitoring data of Shanghai's floating population in 2018, this research uses mathematical statistics and binary Logistic regression models.

Objective: This research analyzes the demographic characteristics and health status of the older adult/adults floating population in Shanghai in the new era and reveals its primary influencing factors.

Results and discussion: (1) A prominent contradiction in the scale and structure of the older adult/adults floating population, with widowed and low-educated mobile older adult/adults requiring attention. (2) There is a lack of health knowledge, and the proportion of local reimbursement is low. Over 90% of migrant older adult/adults self-assessed their health (with a very few unable to care for themselves), far higher than the proportion of older adult/adults who are not sick (injured) or uncomfortable (actually healthy), which exceeds 70%. The health status of migrant older adult/adults deteriorates with age, and those who have never attended school and live alone have the worst health status. (3) Older adult/adults people with advanced age and low educational levels are at risk of health issues, while a better living environment can reduce the risk of illness in the older adult/adults floating population. Low family income, poor housing affordability, and the medical burden brought about by illness can easily lead to older adult/adults floating populations falling into the trap of older adult/adults poverty, and older adult/adults people from central regions and those who migrate along have difficulty adapting to city life, leading to poor self-assessed health. Meanwhile, community/enterprise health education helps to enhance the health protection awareness of the older adult/adults floating population. Finally, based on the governance concept of "mobility publicness," several public management and service optimization strategies for social support for the older adult/adults floating population in Shanghai are proposed.

KEYWORDS

older adult floating population, multidimensional characteristics, health status, influencing factors, Shanghai

1 Introduction

In the context of demographic transition, the older adult floating population has become a new type of mobile group in China. On the one hand, with the extension of life expectancy, people's mobility increases after retirement, making old age a new peak of mobility after a continuous decline in the rate of migration since middle age. On the other hand, with the deepening degree of population aging, the proportion of the older adults in the migrant population is also increasing correspondingly (1). According to the seventh National Census, as of 2020, the older adult population aged 60 and above in China accounted for 18.7% of the total population; the migrant population was as high as 376 million, accounting for 26.6% of the total population. National Bureau of Statistics data shows that in 2021, China's migrant population reached 385 million, while the total population aged 60 and above exceeded 260 million. It is evident that under the dual massive scales of the aging population and the migrant population, the scale of the older adult floating population is rapidly increasing (2).

The older adult floating population, with the dual characteristics of "aging" and "mobility," faces health risks that urgently require the attention of the government and academia. "Aging" signifies a gradual degradation of physiological functions, while "mobility" may bring about issues of environmental adaptation and policy neglect, posing considerable challenges to social governance. Compared to other population groups, the health issues of the older adult floating population have not received sufficient attention and research, and policy concern for the older adult floating population and their health status is relatively inadequate.

Shanghai, as the economic center of the country and a mega-city, is typically representative and significant on the issue of the older adult floating population. A large number of older adult floating population are pouring into Shanghai, putting tremendous pressure on Shanghai's socio-economic development, public services, and eldercare services. The health status of the older adult floating population not only directly affects their quality of life but is also closely related to Shanghai's rational layout of eldercare service facilities, the implementation of social eldercare policies, and the promotion of equal public services. The report from the 20th Party Congress points out: "Promote the construction of a healthy China. Put the guarantee of people's health in a strategic position of priority development, and improve the policy of promoting people's health." Therefore, in-depth research on the health status of the older adult floating population in Shanghai and its influencing factors is beneficial to strengthen policy attention and provide more equitable health services. It is of significant practical significance to provide experiences and references for other cities, improve the health status of the older adult floating population, promote equal public services, and implement healthy aging policies.

The academic community has conducted comprehensive research on the health status of the older adult floating population and the factors that influence it. Current research on the health status of the older adult floating population primarily uses self-assessed health, chronic disease, and daily living self-care abilities to measure health levels, with some researchers focusing on mental and social health (3, 4). Among these, the self-assessed health indicator not only reflects the comprehensive status of subjective and objective, past and present health, but also includes future health status, resistance to disease, and the degree of concern about health (5). Some researchers believe that self-assessed health is even more important than actual medical measurement results (6). Chronic disease indicators can objectively reflect physiological health status. Mental health is generally measured by anxiety or depression scales, and social health refers to the interaction between individuals and others, as well as social systems and customs, and the adaptation to social life (7). Existing research shows that the overall health status of China's current older adult floating population is good, but it is influenced by various factors, and there is still internal differentiation and potential health risks (8–12). The factors influencing the health status of the older adult floating population can be divided into six categories: demographic factors, socio-economic factors, health and medical factors, lifestyle factors, migration factors, and social support factors. In terms of demographic factors, a representative view is that older adult floating populations who are male, younger, and have a stable spouse usually have better health status. Compared with the older adult floating population with a higher level of education, those with a lower level of education have a lower level of self-assessed health and a higher incidence of chronic diseases (13–16). Some research also points out that the health status of middle-aged migrant older adults (70–79 years old) is worse than that of the younger migrant older adults (60–69 years old), and urban household registration migrant older adults can control more health resources, which can buffer the impact of education on health status to a certain extent (17, 18). In terms of socio-economic factors, the health status of older adult floating populations with lower income levels or whose main source of income is family support is usually worse. Health and medical factors are mainly divided into three categories: health education or communication, medical habits, and access to medical resources. A representative view is that health communication significantly promotes the improvement of the health status of migrant older adults through mechanisms such as medical service accessibility, medical service utilization, and health literacy (19). Public health education can also improve the self-assessed health level of migrant older adults, and its impact on the health of rural migrant older adults in the eastern region with high age and high cultural level is greater (20–22). Participating in health check-ups and seeking medical attention for minor illnesses has a positive effect on the health status of migrant older adults. In terms of access to medical resources, the self-assessed health level of migrant older adults who are close to medical places and have established health files is lower (23). Compared with uninsured older adult floating populations, insured older adult floating populations have a higher confirmed rate of chronic diseases. Social health insurance can improve the health level of the older adults. However, some research also shows that social health insurance focuses on economic compensation and has a lag in health protection, and it does not have a significant positive effect on the health of migrant older adults (24). Although insurance has not improved the health status of the older adults or reduced the mortality rate of the older adults, it can significantly increase the utilization rate of outpatient, inpatient, and preventive health care services for the older adults (25, 26). It is worth noting that the probability of migrant older adults using health services is low (27), and there is inequality in the acquisition of basic public health services in terms of identity, region, and city, and the acquisition of basic public health services is at a disadvantage compared to local older adults, and there are differences in urban and rural household registration and differences in the east, middle, and west regions (28, 29). In terms of lifestyle factors, migrant older adults who do not have smoking and drinking habits, exercise for a long time daily, and participate in social activities usually have a higher level of self-assessed health. Quality sleep, longer residence time, and intergenerational consensus have a positive effect on the mental health of the migrant older adult population. In terms of migration factors, a representative view is that older adults with poor health status have characteristics such as long-term mobility, multi-city mobility, mobility with companions, migration for the purpose of caring for family members and older adult care, migrating to remote areas in the northeast or northwest, the size of the city where they migrated to is reduced and the planning direction does not conform to the "dense road network" (emphasize the connectivity, accessibility, and reliability of the road system), and the communication and leisure environment of the community where they live is poor (16–18, 30). Contrary to the conclusions drawn from previous studies, it has been found that the health conditions of the migrant population improve over a longer period of time. This could be due to their adaptation to the culture in the later stages of migration and gaining access to abundant social resources (31). Some research also found that older adults who migrate for the reason of taking care of their descendants have better self-assessed health than those who work and do business, and the self-assessed health level of rural household registration migrant older adults decreases with the increase of migration time, but this effect is not significant for urban household registration migrant older adults. Some studies also point out that population migration affects the mental health of migrant older adults through two opposite mechanisms: health selection and migration risk. In terms of social support factors, the social support network of the older adult floating population shows characteristics of small scale, high closeness, low heterogeneity, and high homogeneity, and the social support network has a direct positive effect on the health of the older adult floating population (8, 15). Specifically, the spousal support, family economic support, and the number of friends in the place of migration have a significant positive impact on the self-assessed health of the older adult floating population, and social interaction and community service levels are important factors affecting the mental health status of migrant older adults (32–34).

At the theoretical level, in view of the characteristics of China's older adult floating population, existing research has combined Western migration theory and general population health-related theory to lay the following foundational understanding for explaining the health status of older adult floating population and predicting future trends. First, as the most important foundational theory in the study of the health of China's older adult floating population, the Healthy Migrant Theory emphasizes the good physical and mental health conditions required for migration, that is, migrants are healthier than those who have not migrated from their original places of residence. Second, Cultural Function Theory and Transnationalism focus on the health of migrants being jointly affected by the cultural forces of both the place of immigration and the place of emigration, which may be realized through social relationships, social support, etc. Third, Social Capital Theory highlights the negative impact of social exclusion and isolation on the health of migrants, and the concept of structural vulnerability also analyzes how administrative irregularities and policies targeting immigrants create unfair socio-political-economic environments that in turn affect immigrant health. Lastly, SDOH (social determinants of health) discusses a variety of processes that may have negative impacts on migrant health, such as overcrowding, environmental health, and multi-level poverty, and also emphasizes the relevance of health with social environment and social strata (35, 36).

Existing research has explored the health status of the older adult floating population and influencing factors, but there are still shortcomings. First, the concept of the older adult floating population is relatively vague. Current research lacks a consistent understanding of age, migration time, and administrative regions crossed by migration, making the conclusions of different studies less comparable (37). Second, existing research shows that the internal heterogeneity of the older adult floating population is high, so it is necessary to group them socially when studying their health, but some research has not grasped this characteristic. In response to the aforementioned shortcomings, this research, based on existing research, believes that the older adult floating population refers to the population aged 60 and above who have left their place of household registration (county-level or above) for 1 month or more without changing the nature of their household registration. Besides, the older adult floating population can be grouped from multiple perspectives to analyze their heterogeneity in this paper, such as dividing them into 5 groups (60–64 years old, 65–69 years old, 70–74 years old, 75–79 years old, and 80 years old and above) from an age perspective. In summary, this study comprehensively analyzes the characteristics and health status of the older adult migrant population in Shanghai in the new era, revealing the main factors affecting the health of the older adult migrant population in Shanghai. It provides empirical evidence for the next step in advancing the policy formulation for the older adult migrant population. The research has significant practical implications for enhancing the attention to the policies of the older adult migrant population, promoting the equalization of public and health services, and responding to the implementation of the proactive strategy to cope with aging at the national level.

2 Methods, variables and data sources

The study utilized a binomial Logistic regression model in the SPSS software to analyze multiple factors affecting the health status of the older adult migrant population in Shanghai. The model formula is as follow (38):

$$Logit(p) = \ln \frac{p}{1-p} \tag{1}$$

$$\ln \frac{P(Y=1|X)}{1-P(Y=1|X)} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \tag{2}$$

In this equation, $P(Y=1|X)$ represents the conditional probability of the dependent variable under the given independent variable X. β_0, $\beta_1 \ldots \beta_n$ are the parameters of the model, where β_0 is the intercept and β_1 to βn are the weights of each independent variable, indicating the degree of influence each independent variable has on the outcome.

Empirical analysis in this paper uses the dynamic monitoring data of the migrant population in Shanghai in 2018 from the "China Migrants Dynamic Survey." The CMDS adopts a hierarchical, multi-stage, and scale-proportional PPS sampling method, taking the non-local population aged 15 and above who have resided locally for more than 1 month as the survey objects. It conducts a detailed investigation of the basic individual and family characteristics of the floating population, as well as the basic conditions of the inflow and outflow areas. The survey covers 31 provinces (regions, cities) and the Xinjiang Production and Construction Corps.

This Research selects the older adult floating population aged 60 and above as the main research objects, with a total of 361 valid samples after screening. To simplify the results of data analysis, besides the overall description, the four options in health self-assessment are grouped into "healthy" (combining "healthy" and "basically healthy") and "unhealthy" (combining "unhealthy, but can take care of oneself" and "unable to take care of oneself"). The questionnaire on the condition of the older adult floating population falling ill (injured) or feeling unwell in the past year is also simplified, combining "fell ill within 2 weeks" and "fell ill more than 2 weeks ago" into "fell ill," and changing "no" to "not ill" (the same rule applies to the related content below). That is to say, in the CMDS survey questionnaire, for the question "Have you ever been sick (injured) or feeling unwell in the past year?," the answers "1 Yes, the last occurrence occurred within 2 weeks" and "2 Yes, the last occurrence occurred 2 weeks ago" are classified as "fell ill "in this article, while the answer "3 No" is considered "not ill." "Self- assessed health" and "actual disease status" are both binary variables, with self-assessed as "healthy" = 1 and "not ill" =1 (see from Table 1). The two outcome variables of health self-assessment and illness status reflect both subjective and objective aspects of the health status of the older adult floating population and are binary variables in this article (5, 7).

Incorporating existing research, theories of social determinants of health (SDOH) and data availability, this study selects individual factors, socio-economic factors, health care factors, and migration factors as explanatory variables (8–25, 35). Shown in Table 1, individual factors include age, gender, education level, and marital status (with or without a spouse); socio-economic factors include household registration type, housing expenditure (divided into high, medium, and low groups, with the low-expenditure group as the reference group), and family monthly income (divided into three types: low income group of 694$ and below, medium income group of 695–2083$, and high income group of 2084$ and above, with the low income group as the reference group). Health care factors include whether to receive community/unit health education and whether to participate in insurance; migration factors include the length of stay in Shanghai (divided into 0–4 years, 5–9 years, 10–14 years, 15–19 years, and 20 years and above, with 0–4 years as the reference group), reasons for migration (divided into working/trading, family migration, visiting friends and relatives, and living in a different place for old age, with working/trading as the reference group), whether there is a willingness to stay, and the province of household registration (divided into east, central, west, and northeast, with east as the reference group). It should be noted that the indicator of the province of household registration reflects the inflow area of the older adult floating population. Existing research has found that the health status of the older adult floating population migrating to remote areas in the northeast or northwest is relatively poor, and because the level of economic development and medical social security in the eastern region is more advanced in China, the eastern region is set as the reference group (17).

TABLE 1 Description of variables.

Types of variables		Variable name and variable description
Outcome variables	Health status	Self-assessed health (self-assessed as "healthy" = 1)
		Disease status (not sick = 1)
Explanatory variables	Individual factors	Gender (male = 1)
		Ages (60–64 years old = 0)
		Education level (never attended school = 0)
		Marital status (without spouse = 0)
	Socio-economic factors	Household registration type (agricultural = 0)
		Household monthly income (low-income group = 0)
		Housing expenditure (low = 0)
	Migration factors	Place of household registration (East = 0)
		Length of stay in Shanghai (0-4 years = 0)
		Reason for migration (working/doing business = 0)
		Willingness to settle (No = 0)
	Healthcare factors	Health education (No = 0)
		Medical insurance (No = 0)

3 Descriptive results of health status and medical security of older adult floating population

3.1 Descriptive results of health and disease status of older adult floating population

3.1.1 Self-assessed health and disease status

From the overall self-assessment results, the health status of Shanghai's older adult floating population is good. As Table 2 shown, the proportion of older adult floating population in Shanghai who self-assessed as "healthy" was 54.1%, and the proportion of those who self-assessed as "basically healthy" was 37.4%, together accounting for 91.5%. Among the older adult floating population who self-assessed as "unhealthy," only 0.7% were unable to take care of themselves, and the majority of older adult floating population, although unhealthy, still have the ability to live independently (To more thoroughly exhibit the distribution of the research subject's self-assessment of health and illness conditions, this section employs the classification types from the original questionnaire).

Compared with the self-assessment results, the proportion of older adult floating population in Shanghai who are ill (injured) or physically uncomfortable is relatively low. As Table 3 shown, the proportions of older adult floating population who became ill (injured) or physically uncomfortable within the last 2 weeks and those before that were 9.6 and 12.3%, respectively, while the

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TABLE 2 Self-assessed health status.

Self-assessed health status	Healthy	Basically healthy	Unhealthy, but able to take care of oneself	Unable to take care of oneself	Total
Proportion (%)	54.1	37.4	7.8	0.7	100.0

TABLE 3 Illness (injury) or physical discomfort.

Illness (injury) or physical discomfort	Sick within 2 weeks	Sick more than 2 weeks ago	No	Total
Proportion (%)	9.6	12.3	78.1	100.0

proportion of older adult floating population who did not become ill (injured) or physically uncomfortable was 78.1%, far lower than the total of those who self-assessed as healthy and basically healthy (91.5%). This suggests that older adult floating population in Shanghai may have overestimated their health status in self-assessment. This may be related to the lack of medical knowledge among the older adult floating population. They are unclear whether the condition of being ill (injured) or physically uncomfortable falls within the scope of health, and mistakenly understand some chronic diseases in the older adults as normal phenomena, resulting in a self-assessed health status that is much higher than the actual non-illness rate.

3.1.2 Self-assessed health status and individual factors

3.1.2.1 Men's self-assessed health is polarized, women are in the middle, but men's actual non-illness rate is higher than women's

Overall, the proportions of men and women among the older adult floating population in Shanghai who self-assessed as healthy are the same, and there is no significant gender difference yet (Table 4). However, a detailed analysis reveals that the proportion of men who self-assessed as "healthy" (58.3%) is higher than that of women (50.5%), the proportion of women who self-assessed as "basically healthy" (41.1%) is higher than that of men (33.3%), the proportion of women who self-assessed as "unhealthy, but able to live independently" (8.3%) is higher than that of men (7.1%), and all those who "cannot live independently" are men (1.2%), with no women. It can be seen that men's self-assessed health status is polarized, with the proportions of "healthy" and "unable to live independently" both higher than women's, while women's self-assessed health status is relatively in the middle, mainly "basically healthy."

Looking at the condition of illness (injury) or physical discomfort among the older adult floating population in Shanghai (Table 5), the proportion of men who have not been ill (healthy) in the past year (80.5%) is higher than that of women (76.0%), and the proportion of women who have been ill (injured) or physically uncomfortable within the last 2 weeks (11.5%) and before that (12.5%) is higher than that of men (7.1 and 12.4%, respectively). This fully demonstrates: the self-assessed health level and actual condition of male older adult floating population are both higher than those of women, but the proportion of men who "cannot live independently" is higher than that of women, and the proportions of women who "can live independently" and actual illness rate are both higher than those of men. This may be related to the traditional concept of "male supremacy and female inferiority." In actual life, female older adult floating population undertake more household chores, and their personalities are relatively gentle, which makes them more likely to feel physically uncomfortable and express their own illnesses (24). Although they often have minor illnesses or chronic diseases, they can still live independently. However, men (especially some young-old who are still working) have greater work pressure, stronger personalities, and are unwilling to express their own emotions. This makes the young-old male migrants who have labor force relatively healthier, while those who have lost their labor force are more likely to suffer from serious illnesses, making it impossible for them to live independently.

3.1.2.2 Divorced older adults have the best health status, followed by first marriage, remarried is worse, widowed is the worst

Shown in Table 6, the health status of widowed migrants is the worst, with the lowest self-assessed health rate (82.2%) and an actual non-illness rate of only 68.9%; the health status of divorced migrants is the best, with the highest self-assessed health rate and actual non-illness rate (100.0% and 87.0% respectively). There is only one unmarried sample among the older adult floating population aged 60 and above, which is excluded from the rankings and detailed analysis.

The impact of marital status on the health status of older adult floating population is mainly manifested in: (1) The self-assessed health of widowed older adults is the worst and the actual non-illness rate is very low, which may be related to the loneliness of widowed older adults when they are ill. In the future, more attention should be paid to the mental health education, emotional comfort and psychological care of widowed migrants. (2) The health status of divorced older adults is better, their self-perception of health is the best, and it is relatively close to the actual illness situation. (3) The illness rate of remarried older adults is the highest, but their self-perception of health is much higher than the actual illness situation. This is mainly related to the greater twists and turns of remarried older adults in marriage, the relatively complex relationship among family members, changes in diet structure and lifestyle, etc. In the future, we need to guide remarried older adults to better integrate into remarried families in terms of thoughts, emotions, and life. (4) The health status of first-married older adults is in the middle, and their self-perception of health is higher than the actual illness situation, and they also need to strengthen their understanding of the category of health.

3.1.2.3 Older adult individuals residing in two-person households exhibit the best health status, while those living alone fare the worst

As Table 7 shown, the health status of older adult individuals living alone is the worst, with both their self-assessed health status and actual rate of disease-free status being the lowest. In households with four residents, the proportion of older adult individuals self-rating

TABLE 4 Health self-assessment status by gender.

Health status	The proportion of male (%)	The proportion of female (%)
Healthy	58.3	50.5
Basically healthy	33.3	41.1
Unhealthy	8.3	8.3
Total	100.0	100.0

TABLE 5 Illness (injury) or physical discomfort by gender.

Illness (injury) or physical discomfort	The proportion of male (%)	The proportion of female (%)
Sick within 2 weeks	7.1	11.5
Sick more than 2 weeks ago	12.4	12.5
No	80.5	76.0
Total	100.0	100.0

TABLE 6 Cross-analysis of marital status and the health status of the older adult floating population.

Marital status	The proportion of self-assessed health (%)	The proportion of who actually not sick (%)
First marriage	92.8	80.2
Remarried	92.3	61.5
Divorced	100.0	87.5
Widowed	82.2	68.9

TABLE 7 Cross-analysis of the number of cohabiting family members and the health status of the older adult floating population.

The number of cohabiting family members	The proportion of self-assessed health (%)	The proportion of who actually not sick (%)
1	71.4	63.6
2	94.4	82.6
3	95.7	78.7
4	96.6	73.3
5	89.9	74.3
6 and above	87.5	75.0

their health is the highest, yet their actual rate of disease-free status is second to last. Older adult individuals in two-person households have the highest rate of disease-free status, with their self-assessed health status ranking third. It is evident that an excessively high or low number of cohabiting family members is detrimental to the physical health of the older adults in the household. When the number of cohabitants is too low (such as in the case of living alone), the older adult individual may feel overly isolated and lack care when ill, leading to the worst self-perception of health. An excessive number of cohabitants can result in complex family relationships and potential physical and emotional exhaustion. A moderate number of cohabitants, between two and four, can both care for the older adults and facilitate harmonious cohabitation, thus promoting the physical health of the older adults.

3.1.3 Self-assessed health and socio-economic factors

3.1.3.1 The health status of older adult floating population with agricultural household registration is better than that of non-agricultural migrants

The self-assessed health status of older adult floating population with agricultural household registration is 92.2%, which is 0.9 percentage points higher than that of non-agricultural migrants. The actual rate of disease-free status is 85.3%, which is 11.3 percentage points higher than that of non-agricultural migrants. This suggests that the older adult non-agricultural migrants in Shanghai are more likely to suffer from chronic diseases such as hypertension and diabetes due to the long-term effects of dietary habits, occupational characteristics, and lifestyle. On the other hand, older adult floating population with agricultural household registration may have better physical fitness due to more physical labor, or they may have a lower use rate of basic public services, leading to missed diagnosis.

3.1.3.2 Individuals with no formal education have the worst self-assessed health, while those with high levels of education have good self-assessed health but a high risk of health issues

According to the self-assessment results (Table 8), among the older adult floating population, those with an associate or bachelor's degree have the highest proportion of self-assessed health, both at 96.7%; those without formal education have the lowest proportion of self-assessed health, at 78.4%. Specifically, the highest rate of "healthy" self-rating is among those with a bachelor's degree, at 60%, while the highest rate of "basically healthy" self-rating is among those with an associate degree (54.8%), and the lowest is among those without formal education (27.0%). This suggests that there is a significant positive correlation between the level of education and self-assessed health.

From the perspective of disease status, older adult floating population with primary school education have the highest disease-free rate, at 85.7%, followed by those with a bachelor's degree (about 83.9%), while those with high school/vocational school education and those without formal education have disease-free rates of 71.9 and 75.7% respectively, ranking last.

Compared to the self-assessment results, the self-assessed health level of older adult floating population with different levels of education is higher than their actual health level. Those with an associate or bachelor's degree have the highest self-assessed health, but their actual disease rate is also high. This may be due to their higher awareness of chronic diseases, but they do not pay enough attention to their impact. Older adults without formal education have the worst self-assessed health, but their actual disease-free rate is not the lowest. This may be due to their dissatisfaction with their health and inaccurate health cognition. Older adult floating population with primary and junior high school education have higher self-assessed health and disease-free rates, which may be related to their relatively low work intensity and slower pace of life. However, it may also be due to their lack of medical awareness and self-care awareness, leading to overestimation of their own health status.

TABLE 8 Cross-analysis of education level and the health status of the older adult floating population.

Education level	The proportion of self-assessed health (%)	The proportion of who actually not sick (%)
Never attended school	78.40	75.70
Elementary school	92.10	85.70
Middle school	95.20	78.80
High school/vocational school	89.60	71.90
Undergraduate	96.70	83.90
Graduate and above	96.70	74.20

3.2 Descriptive results of medical security status of the older adult floating population

The medical security status of the floating population mainly involves issues such as cross-regional medical treatment, participation in medical insurance, and reimbursement.

3.2.1 Hospitalization status

In the 2018 survey of the hospitalization status of the older adult floating population in the past year, only 79 valid questionnaires were obtained. Among them, over 70% of the older adults who were ill were hospitalized in Shanghai, 19.3% were hospitalized in their place of household registration, and 6.9% were hospitalized in other places. This indicates that the cross-regional medical treatment system for the older adult floating population in Shanghai still needs to be improved, with about 30% of the older adults still unable to be treated locally in Shanghai.

3.2.2 Social health insurance

3.2.2.1 Variations in social health insurance participation

In China, the Basic Medical Insurance for Urban and Rural Residents is a policy implemented in certain regions to unify the basic medical insurance coverage for rural residents with local household registration, urban residents with local household registration, and non-local residents. The New Rural Cooperative Medical Insurance is a mutual aid medical insurance system primarily focused on major illnesses for farmers. The Basic Medical Insurance for Urban Residents combines individual contributions with government support and social donations to provide coverage for hospitalization due to major illnesses and special outpatient treatment expenses. Urban Employee Medical Insurance is a form of medical security that involves both the employer and employee, with contributions shared between them, and combines social pooling with individual accounts. The publicly-funded medical care is implemented in China to protect national staff, through which the healthcare departments provide free medical and preventive services to eligible individuals according to regulations. In recent years, with the advancement of the reform of public medical care, relevant personnel will also use medical insurance cards for medical treatment and conduct real-time settlement, similar to basic medical insurance participants.

The highest number of participants in social health insurance is found in the New Rural Cooperative Medical Insurance, accounting for approximately 37.4% of the total. Urban resident medical insurance and urban employee medical insurance both come second, each constituting about 21.3% of the total. The proportion of participants in the basic medical insurance for urban and rural residents is even lower, at 17.7%. The lowest proportion is found in publicly-funded medical care, which only accounts for 2.3%.

3.2.2.2 Reimbursement status of health insurance

3.2.2.2.1 Basic reimbursement situation

The frequency of insurance reimbursements for the older adult floating population in Shanghai is generally low. The highest proportion of reimbursements comes from urban employee medical insurance, accounting for about 41.7%, followed by urban resident medical insurance, accounting for approximately 33.3%. The reimbursement rates for the remaining types of insurance are only about 8.3% each.

3.2.2.2.2 Regional differences in reimbursement

Significant differences exist in the reimbursement of various social health insurance schemes between local areas and places of household registration. In local reimbursements, the highest proportion comes from urban employee medical insurance, at 57.1%, followed by urban resident medical insurance, at approximately 42.9%. Both are higher than their proportions in places of household registration. Publicly-funded medical insurance and basic medical insurance for urban and rural residents have higher proportions in places of household registration (25.0%) than locally (0.0%). The reimbursement rate of the New Rural Cooperative Medical Insurance in both local areas and places of household registration is 0.0%. These findings indicate that the majority of older adult floating population in Shanghai are urban residents (as discussed earlier) and can mostly receive social health insurance reimbursements locally. Among them, working older adult floating population have a higher proportion of urban employee medical insurance reimbursements than non-working older adult floating population. Rural residents are in the minority and must return to their places of household registration for social health insurance reimbursements. The older adult floating population benefits limitedly from social security and welfare, and the reform of social medical insurance in Shanghai and even all over China has a long way to go (39, 40).

3.2.2.2.3 Hospitalization cost expenditure and reimbursement ratio

In general, the reimbursement ratio for older adult floating population in Shanghai is roughly proportional to the cost of hospitalization and medication. In the current sample, based on the exchange rate at the time of writing this article (1 USD = 7.2 Chinese Yuan), the frequency of hospitalization and medication costs between 4,167$ and 12,500$ is the highest (with three people in each category), with individual payments amounting to 2,983$ and 6,944$, respectively, and reimbursement ratios of 50.0 and 66.7%, respectively. The frequency of other hospitalization and medication costs is much lower (only one or zero people). The relationship between individual payments by older adult floating population in Shanghai and hospitalization and medication costs is divided by the boundary of 1,389$. Below 1,389$, individual payments are negatively correlated with hospitalization and medication costs - the lower the hospitalization cost, the higher the individual payment, and the lower the reimbursement ratio. For instance, for an older adult with hospitalization and medication costs of 1,180$, and the reimbursement ratio is 0.0%, meaning that the costs of hospitalization and medication are entirely borne by the individual. However, for an older adult with hospitalization costs of 1,250$, the individual payment is 528$, and the reimbursement ratio is approximately 42.2%. For costs over 1,389$, individual payments are positively correlated with hospitalization and medication costs – the higher the hospitalization cost, the higher the individual payment, but the payment ratio decreases, and the reimbursement ratio increases. For instance, for an older adult with hospitalization and medication costs of 4,861$, the individual payment is 2,778$, and the reimbursement ratio is 57.1%. For an older adult with hospitalization and medication costs of 12,500$, the individual payment is 6,944$, and the reimbursement ratio is approximately 66.7%.

3.3 Descriptive results of community health service status of older adult floating population

3.3.1 Status of establishing resident health records

The proportion of older adult floating population who establish health records is relatively low, as is their awareness of the process. From the perspective of local health record establishment, the proportion of those who have already established records is the lowest, at only 9.7%. Among those who have not established health records, 54.9% have never heard of it, 25.6% have heard of it, and about 9.7% of the older adult floating population are unclear about it. This indicates that while the work of establishing health records has a certain degree of awareness among the older adult floating population, various reasons prevent them from undertaking this task, with some lacking understanding. In future work, those who have heard of it but have not established a record should be targeted for promotion and guidance to increase the proportion of health record establishment. For those who have not heard of it and those who are unclear, efforts should be made to increase publicity and education about the establishment of health records and improve their awareness of health record keeping.

3.3.2 Family doctor contracting status

The highest proportion is "heard of it but did not sign," at 46.3%; the lowest proportion is "signed," at only 3.0%. The proportions of "never heard of it, never signed" and "unclear" are 43.5 and 7.1%, respectively. This is related to the overall low economic income level of the older adult floating population, their insufficient consumption capacity, relatively traditional thinking, and lack of understanding of the advantages of family doctors. The high proportion of "heard of it but did sign" indicates that the older adult floating population has a certain basic understanding. In the future, more publicity and education should be carried out in this regard, allowing more older adult floating population to receive better medical services.

3.3.3 Status of receiving community health education

Table 9 shows that the highest proportion of the older adult floating population in Shanghai receives education on chronic disease prevention and control, followed by public event self-rescue, with the lowest proportion receiving occupational disease prevention and control education. Among them, chronic disease prevention and control health education accounts for 24.8% of the total number of people receiving health education, reflecting the effectiveness of the country's promotion and management of chronic disease prevention and control. The proportion of occupational disease prevention and control education is the lowest, accounting for only 9.4% of health education. The health consciousness of the migrant population is relatively weak, and they often do not consider occupational disease factors when faced with health problems. Increasing occupational disease health education for the older adult floating population can enhance their protective awareness at work, thereby effectively improving the health level of the older adult population.

4 Main factors affecting the health of the older adult floating population

4.1 Model and indicator selection

The primary factors affecting the health of the older adult floating population are analyzed by using the binary Logistic regression model constructed with formulas (1, 2). The dependent variables "self-assessed health status" and "actual disease status" are both binary variables, and the independent variables are all categorical variables. Firstly, individual factors such as the gender, age, educational level, and marital status of the older adult floating population are selected as control variables (Model 1). Based on this, social-economic factors such as household registration, family monthly income, housing expenditure (Model 2), migration factors such as place of origin, length of stay in Shanghai, reasons for migration, willingness to stay (Model 3), and medical factors such as the status and method of receiving community health education, participation in medical insurance (Model 4) are included. Finally, all types of factors are included (Model 5) for comprehensive consideration. The model results are detailed in Table 6.

TABLE 9 The proportion of various disease education in health education.

Types of health education	Proportion (%)
Occupational disease prevention	9.40
Infectious disease prevention	14.80
Reproductive health and maternal and child health	12.50
Chronic disease prevention	24.80
Mental health (including mental disorder prevention)	12.50
Self-rescue in emergency public events	15.70
Others	10.30

4.2 Results analysis

As shown in Table 10, in Model 1, the health status of the older adult floating population is significantly influenced by age and educational level, while gender and marital status do not have a significant impact. In terms of age, the health status of older adult migrant population aged 60–64 is the best, while that of those aged 75–79 is the worst. However, for those over 80, the risk of illness slightly decreases, and health status slightly improves. The older adults in this age group have a lower resistance and recovery ability to diseases, which reduces the proportion of sick individuals to a certain extent. This could also be related to changes in lifestyle and the use of medical services among the older adults as they age. As they grow older, they may pay more attention to healthy eating habits, regular check-ups, and more frequent use of medical services, which could contribute to improving their health status and reducing the chance of illness. In terms of education, compared to the older adult floating population with primary school or lower education, those with junior high school, high school, and college or higher education have a 3.49, 1.61, and 4.90 times higher probability of self-assessed health respectively, indicating a positive correlation between educational level and the health status of the older adult floating population. This could be because the older adult floating population with a higher level of education are more capable of obtaining, understanding, and utilizing health-related information. They may have a better understanding of healthy lifestyles, such as balanced diet, moderate exercise, as well as methods for preventing and managing chronic diseases. Simultaneously, older adult individuals with higher education usually have higher incomes, a higher standard of living, and a greater ability to bear healthcare costs. Moreover, highly educated individuals often have broader social networks, which could provide more social support when facing life's pressures and challenges, benefiting their physical and mental health.

The results of Model 2 indicate that household registration does not significantly affect the self-assessed health and disease conditions of the older adult floating population. Family monthly income only has a slight impact on self-assessed health, while housing expenditure only slightly affects the disease conditions. This suggests that household registration does not cause significant differences in economic conditions and medical resources among the older adult floating population. In terms of income level, the self-assessed health of older adult floating population with moderate household income is better than that of those with lower household income ($p = 0.093$), while the self-assessed health of older adult migrant population with low household income is relatively low. In terms of housing expenditure, the disease risk of older adult floating population with medium housing expenditure is lower than that of older adult floating population with lower housing expenditure ($p = 0.089$), suggesting that a better living environment can reduce the disease risk of the older adult floating population. Specifically, housing conditions (such as ventilation, lighting, and heating systems), living environment (such as air quality), and community services (such as fitness facilities) may all influence the health status of the migrant older adult population. In general, low family income and poor housing conditions are the primary economic factors affecting the health status of the older adult floating population. The medical burden caused by illness also affects family economic conditions and housing affordability, leading to a poverty trap.

The results of Model 3 indicate that the region of migration only has an impact on the risk of illness among older adult floating populations, while the reason for migration only affects the self-assessed health. The duration of residence in Shanghai has an impact on both s self-assessed health and illness status, while the willingness to reside has no significant influence on either of them. From the perspective of the migration region, the disease risk of older adult floating population from the central region is 75.9% higher than that of older adult floating population from the eastern region ($p = 0.082$). This could be due to the lower quality of life and fewer medical resources in the central region, leading to a decline in the physical fitness of the older adult floating population. On the other hand, it could be because the older adult floating population from the central region are not accustomed to the environmental differences after moving to Shanghai. In terms of duration of stay in Shanghai, the self-assessed health results of older adult floating population who have stayed in Shanghai for more than 10 years are worse, and the disease risk increases. The duration of stay in Shanghai is related to the age of the migrant older adult and reflects the long-term negative impact of living in Shanghai on the physical health of the older adult floating population. This could be related to the high population density in Shanghai and the overcrowding of public resources such as medical care and green spaces, which are not suitable for older adult residents. The research also found that the self-assessed health results of older adult floating population who moved for family reasons are worse ($p = 0.086$), which might be related to their difficulty in adapting to the climate, neighborhood atmosphere, and lifestyle of big cities (41). The intention to stay does not significantly affect the self-assessed health and disease conditions of the older adult floating population, indicating that the intention to stay does not affect their health status and quality of life.

The results of Model 4 show that the probability of self-assessed health among older adult floating population who have received community or workplace health education is twice as high as that of those who have not ($p = 0.096$), and their disease risk is 42.8% lower ($p = 0.055$). This suggests that community/workplace health education can enhance the awareness of medical care among the older adult floating population, increase their utilization probability of health service resources, and further improving their health status. Participation in medical insurance does not significantly affect the self-assessed health and disease conditions of the older adult floating population. This could be because the uninsured sample individuals are generally healthier and do not need insurance, or it could be related to the high requirements of insurance for individual age and health status, resulting in a smaller sample size of insured migrant older adult individuals.

After incorporating all variables into Model 5, the impact of individual factors such as age and educational level on the health of the older adult floating population significantly increased. Among socio-economic factors, higher housing expenditure has a negative impact on self-assessed health results ($p = 0.073$). Among migration factors, the duration of stay in Shanghai still has a long-term negative impact on the older adult floating population. Among medical factors, the impact of whether to receive medical education on the health of the older adult floating population has become insignificant, with age and educational level remaining as the main factors affecting the health and disease risk of the older adult floating population.

TABLE 10 The main influencing factors of the health status of the older adult migratory population in the binary logistic regression model.

Variables	Model 1		Model 2		Model 3		Model 4		Model 5	
	Self-assessed	Disease conditions	Self-assessed	Disease conditions	Self-assessed	Disease conditions	Self-assessed	Disease conditions	Self-assessed	Disease conditions
Individual factors										
Male	0.841	0.721	0.917	0.751	0.486	0.859	0.730	0.814	0.448	0.998
Ages										
65–69 years old	0.242**	1.876*	0.244**	1.739	0.256**	1.773	0.263**	1.925*	0.261*	1.772
70–74 years old	0.399	1.137	0.617	0.914	0.601	0.886	0.352	0.986	1.004	0.641
75–79 years old	0.069***	4.843**	0.092**	3.785*	0.128*	2.644	0.064***	5.565**	0.152*	2.527
80 years old and above	0.199	3.104	0.184	2.689	0.366	2.516	0.210	3.159	0.372	2.298
Education level										
Middle school	3.485*	1.242	4.684*	0.978	5.269**	1.025	4.602*	1.229	12.607**	0.792
High school/Vocational school	1.610	1.735	2.113	1.214	1.822	1.763	1.362	1.618	2.026	1.106
Undergraduate and above	4.904*	1.112	6.646*	0.728	6.473*	0.945	3.788	1.437	8.526*	0.742
Marital status										
With a spouse	1.150	0.889	1.039	0.839	1.714	0.729	0.986	0.939	1.025	0.768
Socio-economic factors										
Household registration										
Non-agricultural household registration			1.592	0.590					1.205	0.468
Household monthly income										
Medium-income			2.603	0.872					3.074	0.825
High-income			1.243	1.074					1.304	0.950
Housing expenditure										
Medium			3.455	0.450					3.224	0.511
High			0.459	1.438					0.262	1.590
Migration factors										
Place of household registration										
Central					1.613	1.759			2.301	1.750
West					0.853	1.225			1.504	1.096
Northeast					1.891	1.229			2.410	1.026
Length of stay in Shanghai										
5–9 years					1.182	0.909			1.444	1.025
10–14 years					0.598	1.740			0.853	1.549
15–19 years					0.223*	3.270*			0.169*	3.001*
20 years and above					0.289	1.095			0.278	1.090
Reason for migration										
Family migration					0.314	1.365			0.345	1.013
Visiting friends and relatives					0.503	0.895			0.183	1.206
Aging in a different place					1.573	0.744			0.807	0.692
Willingness to settle										
Yes					1.971	1.099			1.950	1.212
Healthcare factors										
Receive health education										
Yes							2.030	0.572	1.660	0.630
Medical insurance										
Yes							0.770	1.396	1.072	1.461

*represents $p < 0.05$, **represents $p < 0.01$, ***represents $p < 0.001$.

Overall, older adult individuals of advanced age and lower educational level are at health risk. A better living environment can reduce the disease risk of the older adult floating population. Low family income, poor ability to pay for housing, and the medical burden caused by illness can lead to a poverty trap for the older adult floating population. Older adult individuals from the central region and those who migrated for family reasons may have difficulty adapting to life in big cities, resulting in poorer self-assessed health. These situations require serious attention from relevant government departments. Meanwhile, community/workplace health education can enhance the health protection awareness of the older adult floating population. In the future, efforts can be made to further increase health education promotion and encourage more older adult individuals to learn more about health knowledge.

5 Conclusion and policy implication

5.1 Conclusion and discussion

This study analyzes the demographic characteristics and health status of the older adult floating population in Shanghai in the new era, and reveals its main influencing factors. It was found that: (1) Over 90% of the older adult floating population self-rated their health (with only a very small number of older adults unable to care for themselves), which is much higher than the proportion of older adults who are not sick (injured) or physically uncomfortable (i.e., actually healthy) which is over 70%. (2) The health status of the older adult floating population deteriorates with age, and those who have never attended school and live alone have the worst health. The older adult floating population lack health knowledge and have a low proportion of local reimbursement. Widowed and low-educated older adult floating population urgently need attention. (3) The older adult floating population with advanced age and low education level are at health risk. A better living environment can reduce the risk of illness in the older adult migrant population. Lower family income, poor housing payment ability, and the medical burden brought by illness can easily lead to the older adult floating population falling into the poverty trap in old age. The older adult floating population from central regions and migrated older adults have difficulty adapting to life in big cities, which leads to poor self-rated health. Meanwhile, community/unit health education is beneficial to improve the health protection awareness of the older adult floating population.

This article still has some issues need discussion. Firstly, in this study, the probabilities of self-rated health among the older adult floating population with junior high school, high school, and college or higher education are 3.49 times, 1.61 times, and 4.90 times that of those with primary school or lower education, respectively, far higher than the probability multiples of 1.68, 1.79, and 1.61 in another study. The health status differences between the older adults with different levels of education, compared to non-migrants, may result in greater differentiation, which calls for further research (42). Secondly, although some studies have revealed that marriage helps maintain health by protecting people from physical and emotional stress and harmful health behaviors (43, 44), this study did not find a statistically significant difference in the health status of older adult migrants with or without spouses. Some research has pointed out during analysis that compared to rural areas with closer social relations, older adults in Indian cities mostly live in nuclear families, and their health status is more affected by marital status (45, 46). Similarly, it can be speculated that although the reasons for migration vary among the older adult floating population in this study, the act of migration itself implies exposure to new social networks, which might dilute the impact of marital status on health status to some extent. Thirdly, the relationship between family income and older adult health is complex, and the self-assessed health and actual disease conditions of the older adults may also be influenced by various factors such as family atmosphere and relationships among family members, which require further research. Fourthly, although this study did not directly compare and analyze the health status of older adult floating populations with that of ordinary older adults, by comparing the self-assessed health levels of the older adults in this study with those in other research, it was found that the self-assessed health of older adult migrant populations in Shanghai is better than the average level of older adults in China, indirectly indicating that the theory of healthy selection can be used to a certain extent to guide research on older adult floating populations in China (47).

Overall, this research can to some extent reflect the characteristics and health status of the older adult floating population in Shanghai in the new era, and reveal the main factors affecting the health of the older adult floating population in Shanghai. The corresponding countermeasures and suggestions proposed in this study can provide empirical evidence for the next step in advancing the policy formulation for the older adult floating population. The research has significant practical implications for enhancing the attention to the policies of the older adult floating population, promoting the equalization of public and health services, and responding to the implementation of the proactive strategy to cope with aging at the national level.

This study has some limitations too. Firstly, although this study uses the latest batch of data published by CMDS, the survey was conducted in 2018, which may not fully reflect the current situation. As time goes by, the size, structure, and health status of the older adult floating population may change. Secondly, due to data limitations, this study did not explore factors such as social support and cultural adaptation for the older adult floating population. Thirdly, due to the cross-sectional nature of the data, this paper can only engage in a discussion about correlational relationships. Whether there is a causal relationship between influencing factors and health status, as well as specific mechanisms, require further in-depth research and discussion.

5.2 Policy implications

5.2.1 Strengthening the management of the inflow of the older adult migratory population and enhancing integrated supervision, optimizing top-level questionnaire design, and improving the construction of information sharing platforms

The presence and continuous growth of the older adult migratory population in China's major cities, notably Shanghai, is a clear and long-term trend. Government departments should regard this phenomenon as the foundation for the establishment of relevant laws, policies, and systems. The establishment of an internet monitoring system and big data management platform for the older adult migratory population should be prioritized, along with an enhancement of spatial integrated supervision. Policies should ideally lean toward attracting younger, highly educated older adult individuals, thus guiding the balanced development of Shanghai's older adult migratory population. For instance, household registration behaviors of the older adults are selective; compared to those with agricultural identities, non-agricultural older adult individuals are more likely to join the influx into Shanghai.

Simultaneously, departments such as the National Health Commission should further improve data collection work for the older adult migratory population, optimize top-level questionnaire design, particularly in the health sector, and draw from comprehensive international health evaluation indicators to establish a health monitoring mechanism for the older adult migratory population. This mechanism should include exhaustive objective evaluation questions to assess the daily living self-care ability, frailty, and chronic conditions such as hypertension and diabetes among the older adult migratory population. It should also encompass comprehensive surveys on the psychological health, intergenerational family relationships, and social integration of the older adult migratory population.

In addition, the migratory population information management system should be further optimized. Collaboration with higher education population research institutions and experts should be enhanced, aiming to achieve data sharing, integration, and expansion, reduce repeated data entry, and facilitate the conversion of scientific research outcomes. This will provide a scientific basis for government departments to improve social pension, medical insurance, and other policies.

5.2.2 Paying attention to the health status of the older adult with high age and low education, promoting older adult education, and focusing on vulnerable groups such as widowed older adults

The health status is a prerequisite for the mobility of the older adults. The health status of older adult individuals is generally poor, and those with lower education levels lack correct understanding of the relationship between disease types and health status. With increasing age, the rates of self-assessed health and non-illness decline, while the rates of self-assessed unhealthiness and illness rise, indicating that the health status of older adult individuals is poorer. At the same time, there is a clear positive correlation between the level of education and self-assessed health. Older adult migratory individuals who have never attended school have the lowest rate of illness but also the lowest rate of self-assessed health, indicating a lack of correct understanding of the relationship between disease types and health status. The self-assessed health of the older adult migratory population in Shanghai tends to be overly optimistic, with self-perceptions of good physical health often higher than actual illness conditions, and perceptions of poor health far lower than actual illness rates. This is related to the lack of medical knowledge among the older adult migratory population, who often misinterpret some chronic diseases as normal phenomena of aging and self-rate as healthy or basically healthy.

Therefore, relevant departments should strengthen the propaganda of chronic disease prevention and treatment, first aid knowledge, and health preservation knowledge for the older adults, enhance older adults' objective understanding of their own physical health status, and their ability to resist "the risks of longevity." Increased investment in health training in public services and communities/units should be made, making full use of health service resources to improve the health care awareness of the older adult migratory population.

Secondly, government departments such as the Health Commission and the Civil Affairs Department, especially community older adult care service institutions, should pay special attention to widowed and low-educated migratory populations, groups with prominent health risks. They should provide care and policy inclination in health checkups, medical care, community services, home-based older adult care, and government-purchased older adult services to ensure they enjoy relatively fair public social services, safeguard their basic social rights and interests, and enhance the quality of health services for the older adult migratory population.

In addition, given that the rate of widowhood among the older adults with a higher level of education is significantly lower than that of the older adults with a lower level of education, the government and relevant social departments should increase their focus and promote older adult education. This includes education and guidance on psychological health knowledge, early childhood education knowledge, medical first aid knowledge, health preservation knowledge, anti-fraud knowledge, and education on interest-related knowledge such as entertainment, tourism, and finance. This will enhance the cultural level of the older adults, and strengthen their self-protection and health protection capabilities.

Psychological counseling on dealing with the emotional comfort of widowed and retired older adults, the feeling of loneliness from not being able to integrate into city life, and the expansion of interest hobbies should be provided to enrich the spiritual world and quality of life in their later years. This ensures that they can have a healthy and happy later life. Special attention should be paid to the daily life, material, and spiritual care of widowed older adults (especially low-educated female widowed older adults). Efforts should be made to improve their educational level, improve their ideas and methods of caring for grandchildren, enhance their ability to handle family conflicts, alleviate generational conflicts, and enhance their ability to integrate into society.

5.2.3 Accelerating the advancement of the inter-provincial offsite medical insurance reimbursement mechanism, promoting the integrated development of older adult care in the Yangtze River Delta

The health status of Shanghai's migratory older adult population is good, but there are significant differences in the types and locations of social medical insurance participation, and the local reimbursement frequency of various insurances is generally low. With the extension of expected life span, degenerative diseases are gradually becoming potential health risks for the older adult migratory population. However, the insurance status of the older adult migratory population is not optimistic. There are significant differences in the places of participation in social medical insurance, and the proportion of participation in various types of insurance is mainly based on the place of household registration. The reimbursement frequency of all types of insurance is generally low, and the proportion of insurance reimbursements in the local area is much lower than that in the place of household registration (except for urban employee medical insurance). Non-agricultural working migratory older adults who come to Shanghai can mostly carry out social medical insurance reimbursement locally. However, those who are jobless and those with agricultural household registration cannot get medical reimbursement locally and have to return to their place of household registration for social medical insurance reimbursement. It is evident that there is still a long way to go in health knowledge propaganda education and reform of the social medical security system in major cities represented by Shanghai and even nationwide.

Therefore, against the backdrop of the Yangtze River Delta integration rising to a national strategy, government departments at all levels in Shanghai should actively respond to the call of General Secretary Xi Jinping and the Party Central Committee, make the promotion of the integrated construction of older adult care in the Yangtze River Delta a key work of relevant departments in Shanghai, Zhejiang, Jiangsu, and Anhui. Based on the basic reality of regional governance at home and abroad, adhere to the key concept that the key to social governance is the governance of mobility, public relations have mobility, optimize social structure, rationally allocate resources spatially, respect individual mobility decisions and regulate their behaviors, establish the Yangtze River Delta Older adult/adults Association consortium. With the pilot cities as the focus, carry out mutual recognition and research on older adult care needs assessment, older adult service-related standards, and the evaluation system of the older adult care team, establish a mechanism for mutual recognition and promotion of high-quality and trustworthy older adult service brands, and other tasks. The government should formulate policy plans, vigorously strengthen the integrated construction of social older adult care security for the older adult migratory population in the Yangtze River Delta, rationally plan the layout of the Yangtze River Delta older adult service industry, accelerate the construction of integrated medical insurance in the Yangtze River Delta, strengthen inter-provincial offsite medical insurance cooperation, establish a management platform for offsite medical treatment personnel, medical treatment and settlement of accounts, and solve the worries of offsite medical treatment and health care for urban older adult migratory populations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Shanghai Municipal Health Commission. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LW: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing, Data curation, Project administration. WL: Formal analysis, Data curation, Writing – review & editing. SW: Data curation, Software, Methodology, Writing – review & editing. GW: Funding acquisition, Supervision, Writing – review & editing. XW: Data curation, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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A longevity level-oriented wellness target area identification method: a case study of Yunnan Province, China

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Background: Aging, as a global demographic issue, is characterized by its rapid growth, which drives an increase in people's healthcare awareness. The emergence of wellness bases caters to this market demand. Therefore, the identification of potential areas suitable for wellness activities and the construction of wellness bases, referred to as Wellness Target Areas (WTAs), becomes a crucial first step. Currently, commonly used identification methods are mostly based on traditional statistical approaches, which are often complex, cumbersome, and subject to potential risks of subjective assumptions, affecting the reliability of WTAs identification results. Longevity level serves as a comprehensive indicator reflecting the natural and socio-economic environment of a region, making it the most indicative of the regional wellness environment status.

Methods: This study proposes using longevity level as the benchmark for WTAs identification to simplify the identification process and reduce the impact of subjective bias on the results. The study focuses on 129 county-level units in Yunnan Province. Firstly, the Geodetector (GD) is utilized to explore the complex interaction between the longevity level and the geographical environment to determine regional wellness factors. Secondly, using ArcGIS and geographical weighted regression (GWR), the study investigates the role of different wellness factors, ultimately classifying and grading the WTAs.

Results: The longevity level in Yunnan Province exhibits a pattern of multi-point clustering, forming three major longevity regions. Factors that significantly influence longevity level include annual average precipitation, sunshine duration, $PM_{2.5}$ content, per capita disposable income, density of tourist attractions, and distance from residential areas to hospitals. Based on the degree of longevity and the contribution rate of influencing factors, Yunnan Province's WTAs are classified into three levels and two types (natural and comprehensive).

Conclusion: Our study aims to establish a connection between longevity level and the selection of wellness bases, exploring regional wellness factors through the relationship between longevity phenomena and geographical environment, identifying potential construction areas for wellness bases (i.e., WTAs), providing new insights for the precise selection of wellness bases, effectively enhancing the scientificity of site selection, promoting population health, and contributing to the global aging process with better health.

KEYWORDS

longevity population, influencing factor, wellness target area, wellness base, Yunnan Province

1 Introduction

As the global trend of population aging intensifies (1–5), people's awareness of healthcare is gradually increasing. An increasing number of individuals are considering improving their health through various wellness activities, and the emergence of wellness bases caters to this market demand (6–8). The rapid expansion of the aging population, as the primary target clientele, presents significant opportunities and challenges for the development of wellness bases (9–12). They aim to promote physical and mental wellbeing through different environments, experiences, and activities. However, in the current process of constructing and developing wellness bases, various factors need to be considered, such as resource endowment, accessibility, and the income level of the aging population. Additionally, there are issues such as the mere presence of wellness gimmicks, wastage of wellness resources, and unreasonable layouts. Against this backdrop, identifying suitable areas for constructing wellness bases, known as Wellness Target Areas (WTAs), is the crucial first step in their development. This directly impacts the subsequent implementation of wellness activities and the ultimate achievement of wellness goals.

Currently, the identification methods for WTAs primarily rely on qualitative research, while quantitative research is largely based on traditional statistical methods. These methods include Questionnaire Survey Method (QSM) (13), Analytic Hierarchy Process (AHP) (14), and Fuzzy Comprehensive Evaluation Method (FCEM) (15). For instance, Li and Xu (16) evaluated the construction and development potential of forest wellness bases from multiple levels using AHP and FCEM. Liu et al. (17) also used the expert consultation method and AHP to evaluate the suitability of wellness spaces in Beijing, China. Phuthong et al. (18), with the assistance of QSM, formulated assessment indicators for the development potential of Thailand's WTAs from seven dimensions such as infrastructure and cultural resources. Esfandyari et al. (19) evaluated the impact factors of building wellness bases in the rural areas of northwestern Iran based on QSM, asserting that geographical location, climate, history, etc. are the decisive factors for the site selection and construction of wellness bases. However, these methods are often influenced by the subjective thinking patterns of researchers. The question design and interpretation of QSM may be biased due to the subjective preferences and personal opinions of researchers. For example, in the research of WTAs identification, different researchers may have different understandings and definitions of "suitability" and "impact factors," which affects the objectivity of questionnaire design and the reliability of conclusions. Similarly, when AHP and FCEM determine factor weights, they rely on experts to determine the relative importance of each factor through pairwise comparisons, which may lead to inconsistency and inaccuracy of factor weights (20).

In the context of global aging, accurately identifying WTAs suitable for the construction of wellness bases has become an important issue. However, the strong subjectivity and complex selection process greatly limit the effective identification of WTAs. We need to consider using an objective and comprehensive indicator to assess the potential of regional wellness base construction, and use it as a benchmark for WTA identification. From the explanations and elaborations of the concept of "wellness base" by scholars from various fields, it is clear that promoting population health and longevity is the ultimate goal of wellness base construction and wellness activities (21–23). In this regard, the regional longevity agglomeration phenomenon is the result of the comprehensive effect of the natural environment, cultural environment, and individual factors, among others (24–30), and the level of longevity can largely reflect the impact of the regional environment on human health. Therefore, we propose an innovative method, taking the level of longevity as a comprehensive characterization indicator of wellness environment conditions and the main basis for WTA identification. This method aims to establish a connection between the level of longevity and the site selection of wellness bases, explore regional wellness factors through the relationship between longevity phenomena and geographical environment, identify potential construction areas for wellness bases (i.e., WTAs), reduce the impact of subjective bias on the results, avoid the problem of incomplete consideration of influencing factors in the identification process, simplify the complex and cumbersome site selection process, and provide new insights for the precise site selection of wellness bases.

In summary, we use the level of longevity as the benchmark for identifying WTAs and take Yunnan Province, the core area of the longevity region in Southwest China, as the case study. First, we explore the spatial distribution pattern of the longevity a in Yunnan Province through spatial analysis methods. Then, we use the Geodetector (GD) and Geographically Weighted Regression (GWR) to explore the driving factors (wellness elements) that form this pattern (31, 32). The use of GD and GWR is due to their ability to effectively handle the spatial heterogeneity of geographical phenomena, thereby helping us better understand and explain the relationship between longevity phenomena and geographical environment. Through regional wellness elements and their modes of action, we finally divide the potential areas for building wellness bases (i.e., WTAs), into types and levels. This method is expected to provide a reference for the site selection, construction, and development of wellness bases in other regions or globally, meet the wellness needs of various groups mainly composed of older adult, improve the precision of population health policy guidance, and thus promote population health development and contribute to the global healthy aging process.

2 Data source and research methods

2.1 Study area

China, as one of the countries with the fastest aging population in the world, is experiencing a rapid increase in its aging population. According to the 2020 national census data, the population over 65 years old (191 million) accounts for 13.24% of the total population (1.443 billion), an increase of 4.37% compared to 2010. Yunnan Province, as one of the distribution areas of the longevity belt in China, is located on the southeastern edge of the Himalayas (33). The active geological structure movement in the plate boundary area makes it the regional unit with the most diverse geographical

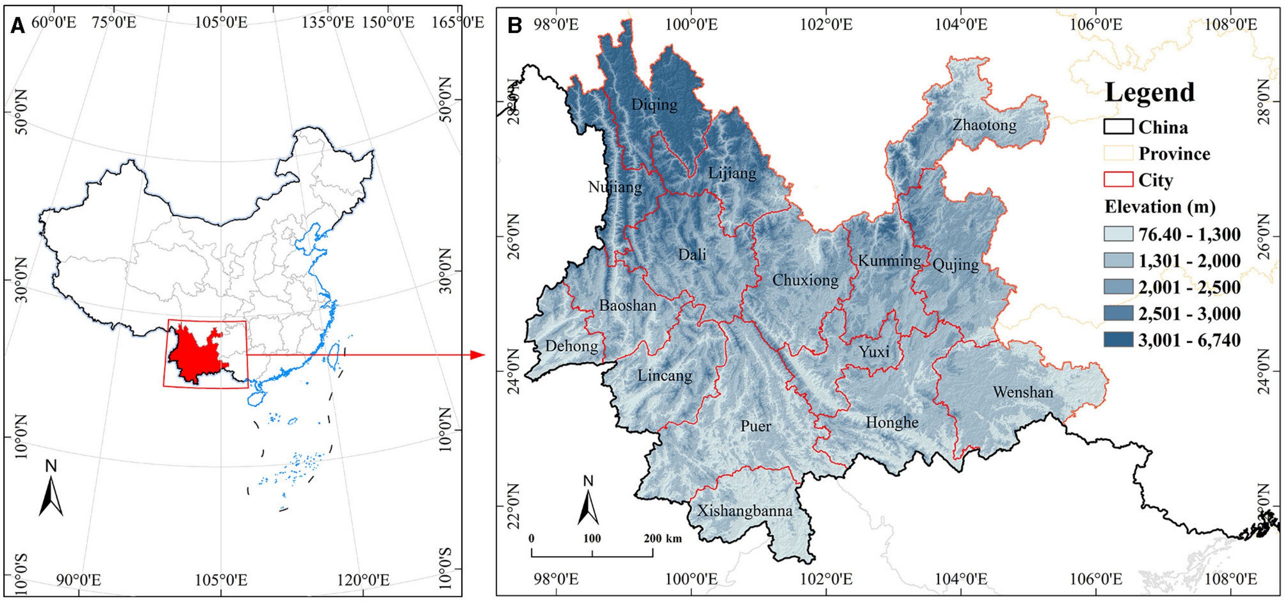

FIGURE 1
Overview map of the study area. **(A)** The location of Yunnan Province in China. **(B)** Diagram of the cities and elevation distribution in Yunnan Province.

environment in Asia, making it an ideal place to study the phenomenon of longevity (Figure 1).

Yunnan Province has a total area of 394,100 square kilometers (21°8′N−29°15′N, 97°31′E−106°11′E). From a natural environment perspective, about 90% of Yunnan Province is mountainous, the terrain gradually descends from the northwest to the southeast in a step-like manner, and the climate is complex and diverse, combining low-latitude climate, monsoon climate, and mountainous climate characteristics. The complex terrain and diverse climate have created unique natural environmental features. At the same time, with the development of the social economy in this area, per capita income is continuously increasing. Influenced by historical and other factors, this area has also formed a multi-ethnic culture (26 ethnic minorities, out of 56 in China), unique health-preserving medicine (Miao medicine, Tibetan medicine, etc.), and other special cultural environments. Ethnic customs and cultural differences also affect the lifespan of the population to a certain extent, which lays a good foundation for regional population longevity (34).

2.2 Data source and preprocessing

2.2.1 Population data

This study is based on the seventh census data of Yunnan Province, with 129 counties in the region serving as the research unit. The vector data is sourced from the National Basic Geographic Information Center (http://www.ngcc.cn/ngcc/), and the population data is derived from the National Bureau of Statistics census data, the China County Statistical Yearbook (County and City Edition), the Yunnan Province Statistical Yearbook (http://www.stats.gov.cn/tjsj/pcsj/), and internal statistical data from various prefecture-level, county-level, and district-level administrative units. The selection of data sources is based on their reliability and timeliness.

2.2.2 Factor data

Longevity is influenced by various factors. Based on the unique natural environment of Yunnan Province and the existing literature on the influencing factors of population longevity, we selected 12 factors for in-depth exploration (18, 35–41). As shown in Table 1, they can be divided into natural and human factors (42). Firstly, terrain and soil conditions are considered to have a certain impact on human health (43–45). Particularly, the impact of elevation and slope on the natural environmental gradients such as air pressure and negative oxygen ions (46). We use the ArcGIS software to extract the average elevation (A_1) and slope (A_2) data of each county from the digital elevation model data (sourced from the Geospatial Data Cloud), and obtains the average soil organic carbon (A_3) content of each county from the World Soil Database to characterize the soil environment. Secondly, high and low temperatures and precipitation intensity in climate factors play an important role in affecting the mortality rate of the older population (47). We use interpolation of nearly 20 years of meteorological station data to obtain the annual average temperature (A_4), sunshine duration (A_5), and annual average precipitation (A_6) of each county from 2000 to 2020. Solid particles in the air, such as $PM_{2.5}$ content (A_7, referring to particles in the atmosphere with a diameter $\leq 2.5\,\mu m$, also known as respirable particles), also have a certain impact on human health (48). In terms of economy, per capita disposable income (B_1) plays a key role in ensuring the quality of life of residents (49). The quality of medical and transportation directly relates to whether residents' health is guaranteed (50). We use the average distance from residents' points to hospitals in each county (B_2) and road density (B_3) to represent these two factors. Finally, the leisure environment for older adult is considered to be closely related to mental health (51), and high-quality older adult leisure environments can improve individuals' emotional regulation ability (52). We use the density of nursing homes (B_4) and density of tourist attractions in each county (B_5) to represent the quality of the leisure environment.

In conclusion, in this study, we have selected a total of seven natural factors (Table 1), including elevation (A_1), slope (A_2), soil organic carbon content (A_3), annual average temperature (A_4), sunshine duration (A_5), annual average precipitation (A_6), average $PM_{2.5}$ content (A_7), as well as 5 human factors, including per capita disposable income (B_1), distance from residential areas to hospitals (B_2), road density (B_3), density of nursing homes (B_4), and density of tourist attractions (B_5) for investigation.

2.3 Methods

2.3.1 Research process

The process of the study is shown in Figure 2. Building upon the elucidation of the coupling relationship between the spatial distribution of longevity levels and the identification of wellness factors, this study focuses on the core area of the typical longevity belt in China, namely Yunnan Province, as a case study area. It investigates the spatial distribution patterns of longevity levels and employs GD model to explore the driving factors behind this distribution pattern (i.e., identifying regional wellness factors). Due to variations in the depth and breadth of the effects of different wellness factors in different regions, the study further utilizes GWR to investigate the modes of action of different driving factors on regional longevity levels. Based on the regression coefficients, the contribution of different factors is calculated to classify the types of WTAs. Meanwhile, based on the longevity index, these WTAs are graded, leading to conclusions being drawn.

2.3.2 Longevity index

The level of longevity can be measured from multiple perspectives, and its measurement methods involve various indicators. To more comprehensively assess the longevity status of a region or country, it is often necessary to consider multiple factors (30). This study starts from the perspective of the structure of the aging population and measures the regional longevity level by the percentage of the population over 90 years old (P_{90+}) to the population over 65 years old (P_{65+}). This calculation method can not only avoid the impact of the population base, but also more specifically understand the longevity status of a region in the higher age segment, and intuitively reflect the overall lifespan level of the region (53). The longevity index is calculated as shown in Equation (1):

$$Longevity\ index = \left(\frac{P_{90+}}{P_{65+}}\right) \times 1000 \tag{1}$$

2.3.3 Hotspot analysis

Hotspot analysis is a statistical technique that uses the Getis-Ord G_i^* index to identify areas with significant spatial clustering of high or low values. This allows for the measurement of cold spots and hotspots in geographical phenomena (54). In this study, the G_i^* index is used to measure and evaluate the spatial clustering degree of the longevity index. The G_i^* index is calculated by Equation (2):

$$G_i^* = \sum\nolimits_{j=1}^{n} W_{ij}X_i / \sum\nolimits_{i=1}^{n} X_i \tag{2}$$

After standardizing the G_i^* index, $Z(G_i^*)$ is obtained, and the calculation formula is as Equation (3):

$$Z\left(G_i^*\right) = \left[G_i^* - E\left(G_i^*\right)\right] / Var\left(G_i^*\right) \tag{3}$$

In the formula, X_i represents the longevity index of the ith county in Yunnan Province. W_{ij} is the spatial weight matrix. n is the total number of evaluation units (number of counties). $E(G_i^*)$ is the mathematical expectation. $Var(G_i^*)$ is the coefficient of variation. The distribution of the $Z(G_i^*)$ values determines the hot and cold spot areas of the longevity index in different counties. If the $Z(G_i^*)$ value is significant and positive, it indicates that the longevity population in that area shows a high-level spatial clustering feature, making it a hot spot area. Conversely, if it is a negative value, it indicates a cold spot area.

2.3.4 Geodetector

GD model is a statistical method that reveals the driving factors behind research phenomena and the interaction relationships between various factors (32). GD includes risk detection, factor detection, ecological detection, and interaction detection. According to the research needs, this study only explains factor detection and interaction detection, which respectively represent the explanatory power (q) of single factor or multi-factor interaction on the spatial differentiation of longevity population. The establishment of the GD model requires the conversion of continuous variables into discrete categories or interval variables. This study inputs 12 geographical environment variables into GD to calculate q-values. It utilizes the GD package in R (55) to draw distribution maps of q values obtained through various discretization methods (including equal interval, quantile, natural breakpoint, geometric interval, and standard deviation methods) and classification numbers (ranging from 4 to 10 classes). The study identifies the optimal discretization method for different factor variables based on the maximum q value. The calculation formula of q is as Equation (4):

$$q = 1 - \frac{SSW}{SST} = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \tag{4}$$

In the formula, q represents the explanatory power of geographic factors for spatial heterogeneity of longevity population, with a range of [0, 1]. A higher q-value indicates stronger explanatory power. L is the number of categories of the influencing factor X, N_h is the total number of units in the entire region (number of counties), and σ_h is the variance of the dependent variable Y for the hth category within the region.

2.3.5 Geographically weighted regression

The Geographically Weighted Regression (GWR) model is a regression model that extends spatial effects based on the

TABLE 1 Impact factor parameters and their data sources.

Dimension	Factor type	Factor	Code	Data source
Natural geographical environment	Topography	The average elevation (m) of each county	A_1	The digital elevation data products were obtained from the Geospatial Cloud (https://www.gscloud.cn/)
		The average slope (°) of each county	A_2	The digital elevation data products were obtained from the Geospatial Cloud (https://www.gscloud.cn/)
	Soil	The average soil organic carbon content (%) for each county	A_3	The soil data were obtained from the Harmonized World Soil Database (HWSD) (https://www.fao.org/)
	Climate	The annual average temperature (°C)	A_4	The meteorological data were sourced from the National Meteorological Data Center (https://data.cma.cn/)
		Sunshine duration (h)	A_5	The meteorological data were sourced from the National Meteorological Data Center (https://data.cma.cn/)
		The annual average precipitation (mm) of each county from 2000 to 2020	A_6	The meteorological data were sourced from the National Meteorological Data Center (https://data.cma.cn/)
	Air quality	The average $PM_{2.5}$ ($\mu g/m^3$) for each county	A_7	The $PM_{2.5}$ data were obtained from the Atmospheric Composition Analysis Group at Washington University in St. Louis (https://sites.wustl.edu/)
Human geographical environment	Economy	Per capita disposable income (yuan/person) in 2020 for each county	B_1	Data from Yunnan Statistical Yearbook (http://stats.yn.gov.cn/)
	Medical care	Average distance (km) from residential areas to hospitals in each county	B_2	The directory of medical institutions is sourced from the National Healthcare Security Administration Service Platform (https://fuwu.nhsa.gov.cn/)
	Transportation	Average road density in each county	B_3	Road vector data is obtained from OpenStreetMap (https://www.openstreetmap.org/)
	Nurse	Average density of nursing homes in each county	B_4	Nursing home institution directory is sourced from the Yunnan Provincial Civil Affairs Department (https://www.ynmz.yn.gov.cn/)
	Leisure	Average density of tourist attractions in each county	B_5	The POI data for tourist attractions were filtered and processed, resulting in a total of 8,510 records extracted (https://www.djyanbao.com/)

Ordinary Least Squares (OLS) model (31). It is used to study the relationships between variables in spatial datasets and takes into account spatial autocorrelation. Unlike traditional regression analysis, GWR allows model parameters to vary spatially, meaning each observation point (county) in the model has its own regression coefficient. This enables GWR to better capture the spatial heterogeneity and non-linear relationship between the spatial distribution of the long-lived population and influencing factors. In GWR, the regression coefficient of each observation point (county) is calculated by weighting the information of nearby points, these weights are usually calculated based on distance or other measures of spatial association. Therefore, for each observation point, the model fits a local regression model based on the data of its surrounding neighboring points to more accurately reflect the specific spatial environment of that point (county). The calculation formula for the GWR model is as Equation (5):

$$y_i = \beta_0 (\mu_i, v_i) + \sum_k \beta_k (\mu_i, v_i) x_{ik} + \varepsilon_i \tag{5}$$

In this formula, y_{i} represents the longevity index, P is the number of wellness factors, (u_i, v_i) represents the coordinates of point i $(i = 1, 2, 3, \ldots, n)$, and $\beta_k(u_i, v_i)$ is the value of the continuous function at point i. x_{ik} and ε_i denote the kth independent variable and its error term, respectively.

This study, based on the comprehensive consideration of the geographical environmental characteristics and socio-economic status of Yunnan Province, uses GD to screen out factors that have a significant correlation (above 95% confidence level) with the phenomenon of longevity areas. Since different factors have obvious differences in their effects in different regions, WTAs are further classified and graded based on the results of the GWR

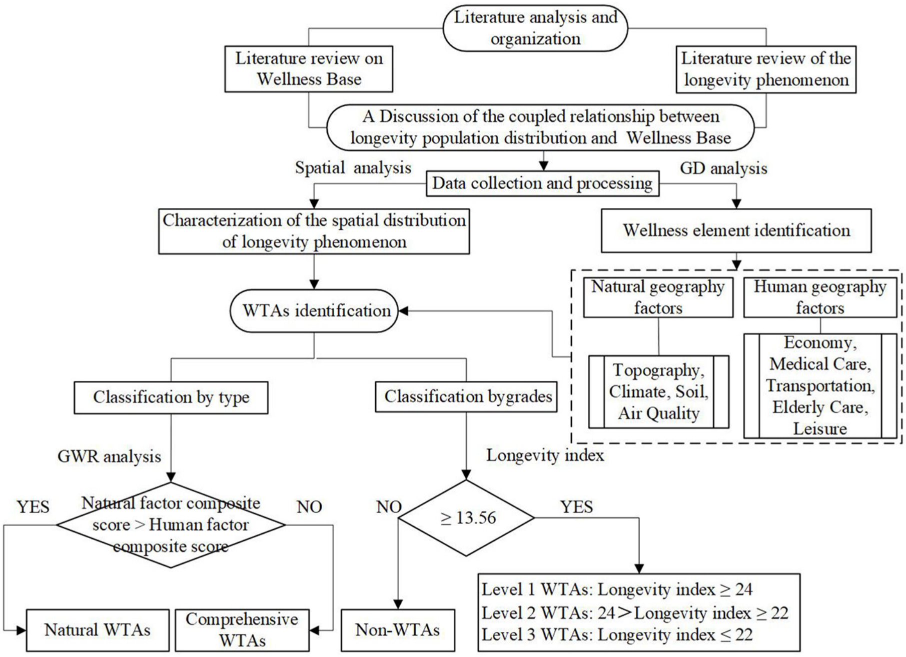

FIGURE 2
Research flowchart.

regression coefficients. GWR is performed in ArcGIS software, and the specific steps are as follows:

- First, normalize the values of the influencing factors that pass the significance test (in the GD model).
- Next, calculate the sum of the products of the contribution (regression coefficient) of different types of influencing factors (natural factors and human factors) through the GWR model to obtain the comprehensive scores of natural factors and human factors in different counties.
- When the comprehensive score of natural factors in a certain county is higher than the comprehensive score of human factors, it is classified as a natural type WTA, otherwise, it is classified as a comprehensive type WTA.

3 Results

3.1 Spatial distribution characteristics of longevity level

To circumvent the influence of population differences on the spatial differentiation of longevity, we use the longevity index (in Section 2.3.2) to measure regional longevity levels and conduct spatial visualization analysis (Figure 3A). The study uses the national average level of 15% as the threshold, dividing the longevity area into four levels, namely high-level area (27.70–33.4), sub-high-level area (24.09–27.69), higher-level area (20.48–24.08), and non-significant area (11.47–20.47). The regional differences in the longevity index at the county scale are significant, and the high-level areas show a "three poles and multiple centers" distribution trend.

The "three poles" are clustered around Dian Lake, Nujiang, and Honghe River, presenting three major longevity areas: (1) The "Dian Lake Basin Longevity Area" (Figure 3B), which includes high-level and sub-high-level and higher-level areas surrounding the high-level area (Wuhua and Panlong), overall showing a hierarchical distribution. (2) The "Nujiang River Basin Longevity Area" (Figure 3C), which includes a high-level county (Fugong), multiple sub-high-level areas (e.g., Gongshan) and higher-level areas (e.g., Tengchong) distributed near both sides of the Nujiang River. (3) The "Honghe River Basin Longevity Area" (Figure 3D), where sub-high-level areas (e.g., Pingbian) and multiple higher-level areas are distributed around the high-level area (Gejiu, Jinping, Xichou), presenting a hierarchical distribution. The "multiple centers" are manifested as counties such as Linxiang (Figure 3E), Menghai (Figure 3F), and Luoping (Figure 3G), which are clustered or sporadically distributed sub-high-level longevity areas.

To further explore the clustering pattern of longevity, the Getis-Ord G_i^* statistical index-based hotspot analysis method was employed in the ArcGIS platform. The spatial results of the hotspots for the longevity index in Yunnan Province are shown in Figure 4. Hotspot areas [including highly significant hotspots (99% confidence level), significant hotspots (95% confidence level), and hotspots (90% confidence level)] are mainly distributed in the Dian Lake Basin, the Honghe River Basin, and the Nujiang River Basin, with highly significant hotspots mostly concentrated in the Honghe River Basin and the Dian Lake Basin. Coldspot areas [including highly significant coldspots (99% confidence level), significant coldspots (95% confidence level), and coldspots (90%

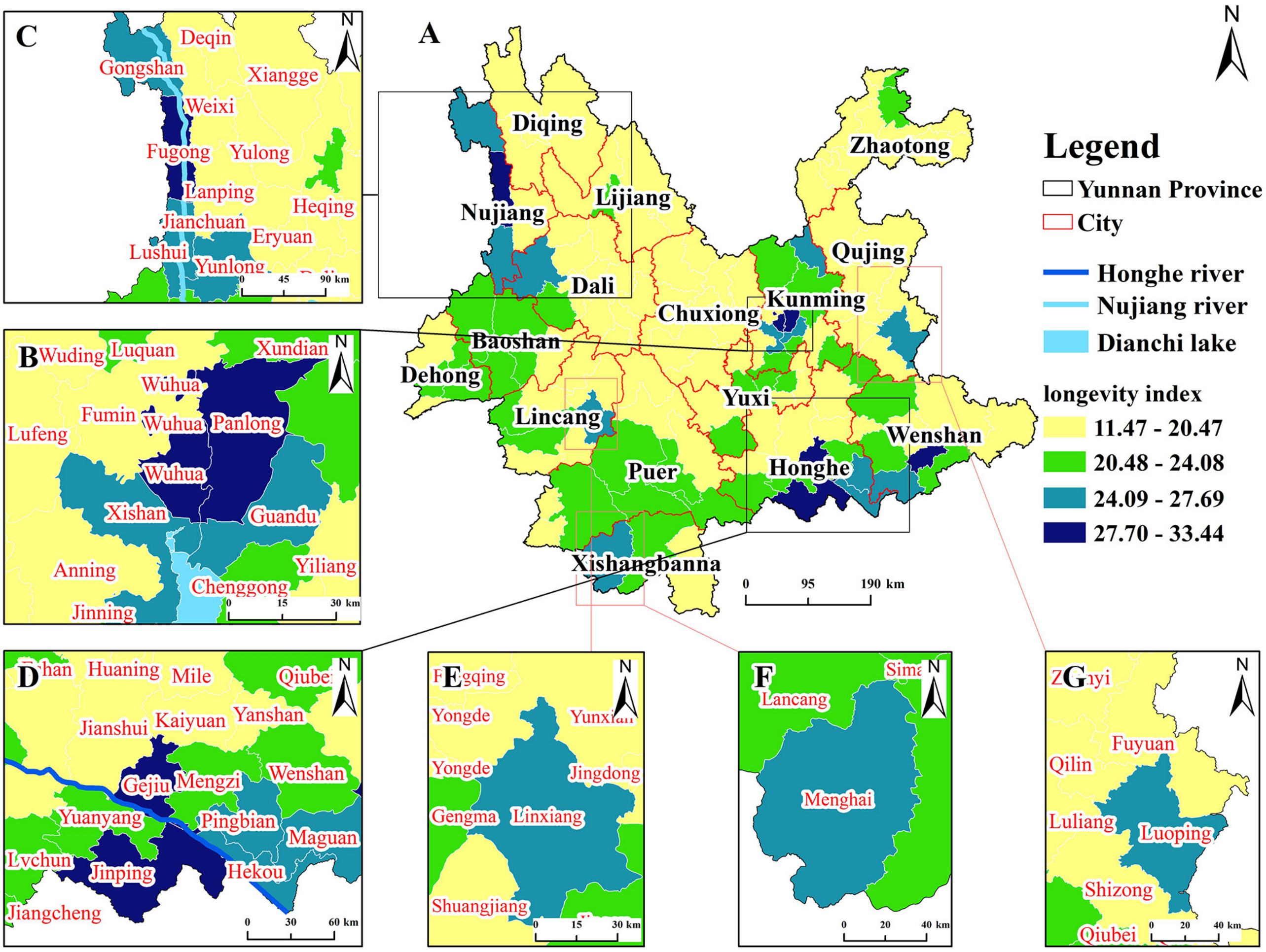

FIGURE 3
Distribution map of longevity levels (index), showing the following: **(A)** Distribution map of longevity index in Yunnan Province; **(B)** Dian Lake Basin Longevity Area; **(C)** Nujiang River Basin Longevity Area; **(D)** Honghe River Basin Longevity Area. **(E)** Linxiang and other secomd-level areas; **(F)** Menghai and other secomd-level areas; **(G)** Luoping and other secomd-level areas.

confidence level)] are mainly located in areas such as Dali City, Chuxiong City, and Zhaotong City. The results of the hotspot analysis correspond to the geographical distribution characteristics of the longevity index. It can be observed that longevity regions are mainly concentrated in the Dian Lake Basin, Honghe River Basin, and Nujiang River Basin.

3.2 Geodetector results

Using the longevity index as the dependent variable, the natural and human factor variables were transformed into type values and inputted into the GD model for calculation. The best detection results were then output based on different discretization methods.

The results of single-factor detection are depicted in Figure 5. From the perspective of natural factors, significant differences in the contribution of each factor are observed. The influence on the spatial distribution of the longevity population follows the order of A_6 (0.2816) > A_5 (0.2624) > A_7 (0.2108) > A_1 (0.1506) > A_4 (0.0987) > A_2 (0.0649) > A_3 (0.0293). Notably, A_6 (0.2816) exhibits the highest contribution to the spatial agglomeration of the longevity population, while factors A1, A_2, A_4, and A_3 did not pass the significance test ($p < 0.05$). Regarding human factors, the influence on the spatial distribution of the longevity population follows the order of B_3 (0.2639) > B_1 (0.1833) > B_4 (0.1757) > B_5 (0.1686) > B_2 (0.1537). However, both B_3 and B_4 did not pass the significance test ($p < 0.05$). Overall, the explanatory power q of the six factors that passed the significance test is as follows: $A_6 > A_5 > A_7 > B_1 > B_5 > B_2$, indicating that the explanatory power of natural factors is stronger than that of human factors. This underscores the crucial role of natural factors, as innate environmental conditions, in determining the longevity level.

The GD interaction detection results, as illustrated in Figure 6, indicate that the interaction between A_5 and A_4 is the most significant ($q = 0.601$). A_6 and B_5 constitute the second leading interaction factors for the distribution of high longevity levels ($q = 0.531$), while A_5 and B_5 are the third leading interaction factors ($q = 0.530$). Notably, although the explanatory power of A_4 is not significant in single-factor detection, its interaction with A_5 yields the highest action value at 0.601. This suggests that

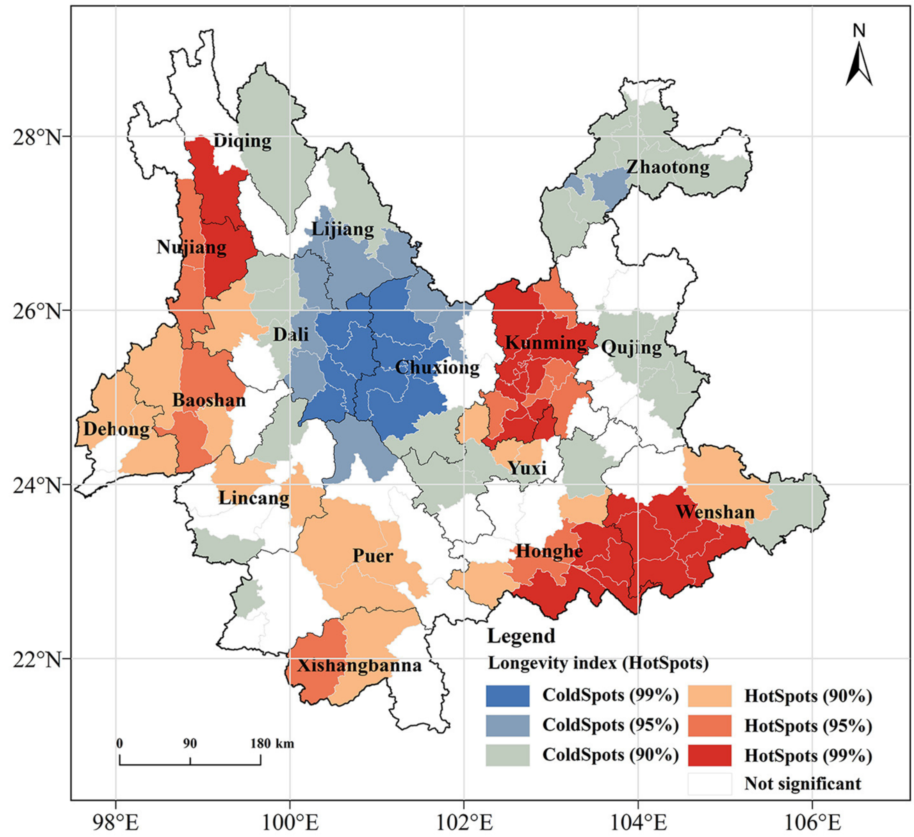

FIGURE 4
Hotspots distribution map of longevity level (index).

the explanatory power of dual-factor interaction surpasses that of single-factor action, indicating that spatial heterogeneity results from enhanced effects after multi-factor interaction. When A_5 and A_6 interact with multiple human factors, the action values are all above 0.45, indicating that the explanatory power for the spatial agglomeration of the longevity population is significantly improved when human factors interact with natural factors. In conclusion, while natural factors play a leading role in longevity agglomeration, the influence of human factors should not be overlooked. The explanatory power of geographical factor interaction on the spatial distribution of longevity levels does not follow a linear influence of a single factor or a simple superposition process, but rather results from multi-factor comprehensive action.

3.3 Geographical weighted regression results

Given that the impact of different factors on the spatial distribution of the long-lived population is not isolated, and the strength and outcome of independent variables vary across regions, the GWR model was further introduced for local spatial regression analysis. The spatial differences in the effects of six influencing factors that passed the 0.05 significance test of geographic detection were analyzed, including three natural factors (Factor A_6, A_5, and A_7) and three human factors (Factor B_1, B_2, and B_5). The GWR model overall passed the multicollinearity judgment, with an R^2 of 0.5320 (adjusted $R^2 = 0.4438$), indicating a relatively high goodness of fit. The spatial effects of each geographic factor were significantly different, as shown in Figure 7.

The GWR analysis reveals that natural factors exert varying positive and negative influences across different regions. Factor A_6 significantly positively affects the spatial distribution heterogeneity of the longevity population, with the effect intensifying from the south to the north of Yunnan Province. This suggests that precipitation has fostered longevity in Yunnan Province, with rainfall's contribution to longevity being more pronounced in the north. Conversely, Factor A_5 negatively impacts the western region of Yunnan Province. These areas, despite having a basic sunshine duration exceeding 5.5 h, experience a negative effect due to low rainfall. However, it exerts a positive influence in the east and northeast of Yunnan Province. These regions, located in the front zone of the Kunming quasi-stationary front, receive high rainfall, and the appropriate sunlight promotes health preservation. The influence of Factor A_7 diminishes from the southeast to the northwest of Yunnan Province. The lower the $PM_{2.5}$ content level, the higher the air quality, which is beneficial to human health. The $PM_{2.5}$ content concentration across Yunnan Province is generally low, with only Hekou County's $PM_{2.5}$ content concentration

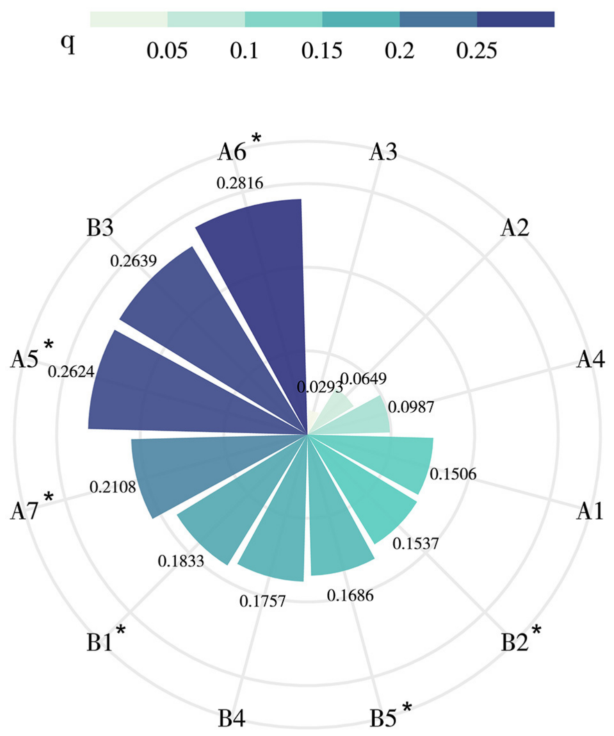

FIGURE 5
Single factor detection results affecting the spatial distribution of long-lived population. "*" represents a significant p-value < 0.05 (i.e., passed the test of significance).

(36.842 μg/m^3) exceeding the national secondary standard (35.000 μg/m^3) (56). The positive effect of the regression coefficient in the southeastern region may be attributed to the minimal social and economic development gap in these areas. Residents can access equal opportunities for medical, educational, and other facility services. In recent years, the economic growth rate has gradually increased, and industrial pollution has intensified. Consequently, a contradiction between high $PM_{2.5}$ content concentration and high longevity level has emerged.

The GWR results also indicate that human factors exert varying positive and negative influences across different regions. The regression coefficient of Factor B1 has a significant positive driving effect in approximately half of the study areas, primarily concentrated in the 100°E−102°E region, such as Xishuangbanna City, Dali City, and Lijiang City. This is attributed to the development of the tourism industry in these areas in recent years, which, coupled with economic development, has fostered longevity. The areas negatively impacted by Factor B_1 are concentrated in the southeastern region of Yunnan Province. These areas, despite being relatively economically underdeveloped, have a high longevity index, hence the negative impact. With the exception of a few counties near the southwestern border of Yunnan Province that do not contribute positively, Factor B_2 has almost universally limited the improvement of longevity in all areas. This is because the population in the southwestern region of Yunnan Province is relatively small, and medical resources are not as strained as in other places, resulting in a weak impact of B_2 on the clustering of longevity. Factor B_5 has a significant positive effect in all counties in Yunnan Province. Yunnan, boasting a large number of tourist attractions and ranking among the top in the country, has a rich ethnic cultural atmosphere that promotes both physical and mental health.

3.4 Wellness target area identification results

The GD analysis explores the impact of various factors on longevity across geographical spaces, while the GWR more finely discerns the contribution (regression coefficient) of different factors to longevity in distinct regions. Therefore, calculating the weight scores of natural and human factors based on their contributions is a logical approach. This method quantifies the impact of different factors and provides a foundation for the subsequent identification and classification of WTAs.

Based on the above conclusions, this study adopts A_6, A_5, A_7, B_1, B_2, and B_5 as the selection criteria for WTAs, which is scientifically sound. Specifically, this study first identifies the main factors that significantly impact the longevity level and identifies the regional healthcare elements (including A_6, A_5, A_7, B_1, B_2, and B_5) based on the results of the GD analysis. Then, through GWR, the contribution of each factor in geographical space (i.e., regression coefficient) is explored to obtain more regionally differentiated factor weights. Finally, the comprehensive scores of natural and human factors in different counties are calculated respectively, based on the sum of the product of the normalized source data of the influencing factors and their contributions. These scores are combined to categorize different types of WTAs. If the comprehensive score of natural factors in a county is higher than that of human factors, it is classified as a natural WTA; otherwise, it is classified as a comprehensive WTA.

Simultaneously, counties (55 in total) not <15% of the national average longevity level are classified and graded, and the division results are shown in Table 2 and Figure 8. Natural WTAs are primarily distributed in the northwest and southeast of Yunnan, while comprehensive WTAs are mainly located in the central region of Yunnan. Among them, first-level WTAs (longevity index ≥24) include 18 counties, comprising 10 natural WTAs and 8 comprehensive WTAs; 16 counties are categorized as second-level WTAs (24 > longevity index > 22), including seven natural WTAs and nine comprehensive WTAs; third-level WTAs (longevity index ≤22) include 20 counties, divided into 11 natural WTAs and nine comprehensive WTAs.

4 Discussion

4.1 Distribution characteristics of longevity and identification of WTAs

In terms of the spatial distribution of longevity, we found that the longevity regions in Yunnan Province exhibit a "three-pole and multi-center" distribution pattern. These areas also display a distinct "center-periphery" distribution mode, which roughly corresponds to the economic geography gradient of Yunnan

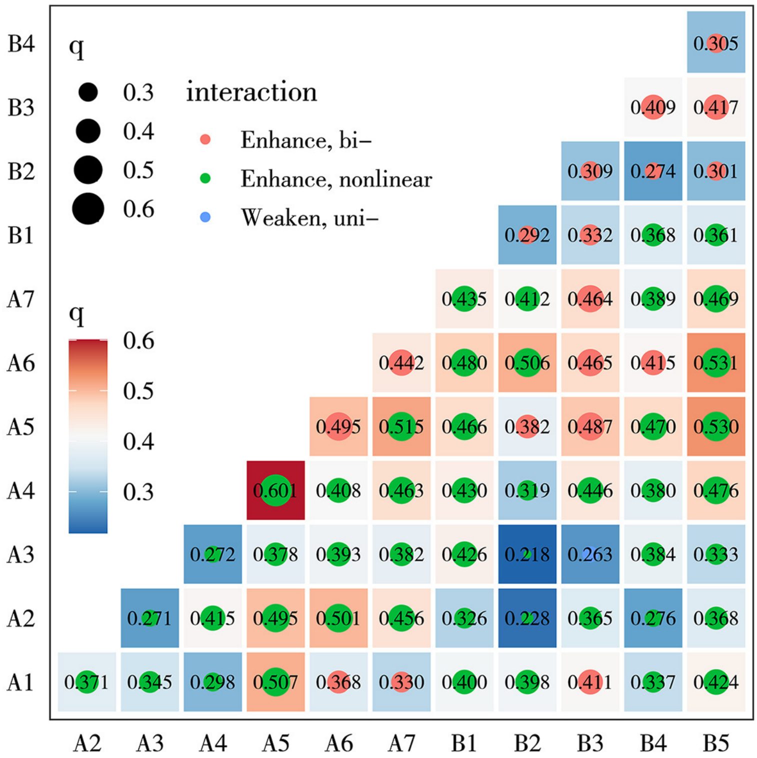

FIGURE 6
Heat map of interactive detection of influence factors. Natural factor (code): elevation (A_1), slope (A_2), soil organic carbon content (A_3), annual average temperature (A_4), sunshine duration (A_5), annual average precipitation (A_6), and average $PM_{2.5}$ content (A_7). Human factors: per capita disposable income (B_1), distance from residential areas to hospitals (B_2), road density (B_3), density of nursing homes (B_4), and density of tourist attractions (B_5).

Province but is not entirely coincident. This indicates that the phenomenon of longevity is influenced by a combination of the natural environment and socio-economic conditions. The results of the GD further confirm this rule: the explanatory power of natural factors for the phenomenon of longevity is slightly stronger than that of human factors. The explanatory power of factors, as determined through significance testing, is in the order of annual average precipitation > sunshine duration > $PM_{2.5}$ content > per capita disposable income > density of tourist attractions > the average distance from residents' points to hospitals. It can be seen that as innate environmental conditions, natural factors are crucial to the level of longevity, but the driving role of human factors should not be ignored. On the other hand, the results of GWR also show that due to geographical environmental differences, independent factors (variables) have different strengths and results in different regions. There are positive and negative differences in the spatial effects of each geographical factor on the longevity index.

Through the analysis of longevity level characteristics, we use the national average longevity level as a basis to divide it into three levels. As mentioned earlier, the phenomenon of longevity is influenced by the spatial heterogeneity of natural and human factors in different regions. Therefore, WTAs should also be divided into different types based on this heterogeneity phenomenon. We calculate the comprehensive scores of different factor types (natural and human) based on their contributions, and finally divide the WTAs in Yunnan Province into two types: natural and comprehensive. The first-level natural WTAs are mainly distributed in the northwest, southwest, and southeast of Yunnan. These areas, dominated by mountains and hills, have a warm and humid climate, and a dense river network. The unique natural resource endowment makes these areas the core of longevity population agglomeration, providing a positive effect for the agglomeration of the longevity population. The first-level comprehensive WTAs are mainly distributed in the central region of Yunnan. This area, characterized by a flat and open terrain and a warm and humid climate, meets the health needs of the wellness group given the natural environment. A robust economic foundation can also meet the market demand of the wellness group for modern social service levels, and radiate to drive the economic development of surrounding areas.

4.2 Issues and policy suggestions for the identification of WTAs

Currently, there are still many issues in the identification of WTAs globally, and the construction of wellness bases remains in an immature stage (1, 2, 57). Based on the analysis of literature from various countries and the case area (Yunnan Province, China), the common problems faced can be summarized as follows: (1) In the geographical environment, health and wellness factors have

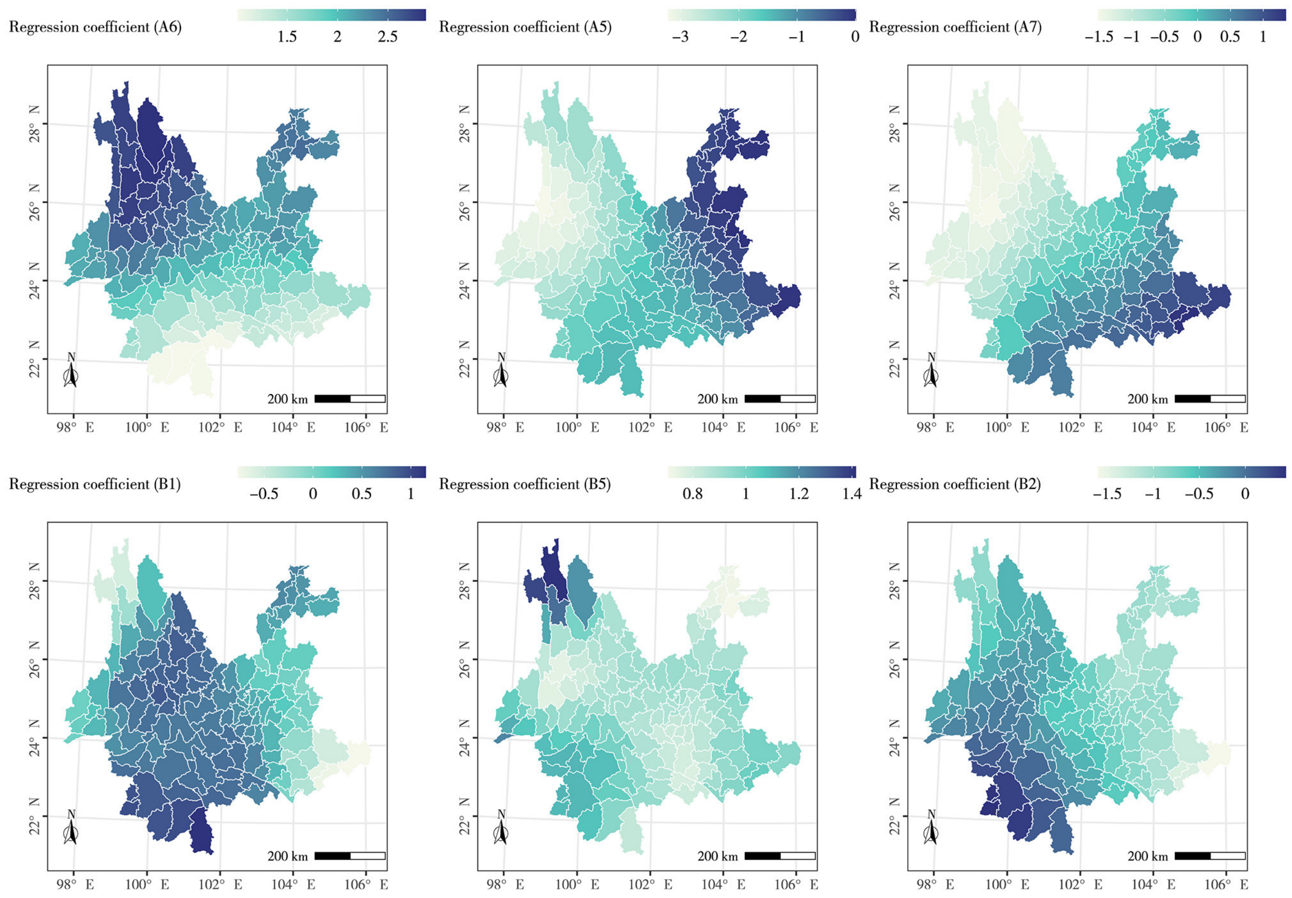

FIGURE 7
Analysis of regression coefficient of impact factors. showing the following: Geographically weighted regression analysis of human factors: Natural factor (code): the annual average precipitation (A_6), sunshine duration (A_5), and average $PM_{2.5}$ content (A_7). Human factors: the per capita disposable income (B_1), distance from residential areas to hospitals (B_2), and density of tourist attractions (B_5).

TABLE 2 Classification table of wellness target areas (WTAs) in Yunnan Province.

Level	Longevity index	Natural WTAs	Comprehensive WTAs
Level 1	≥24	Fugong, Jinping, Xichou, Pingbian, Maguan, Lushui, Menghai, Linxiang, Hekou, Luoping	Wuhua, Gejiu Panlong, Xishan, Gongshan, Dongchuan, Guandu, Yunlong
Level 2	22–24	Wenshan, Malipo, Shidian, Lianghe, Shuifu, Simao, Yanjin	Longyang, Ashan Xundian, Jinghong, Songming, Jinning, Chenggong, Luxi, Mengzi
Level 3	≤22	Longling, Mangshi, Lancang, Longchuan, Zhenkang, Jinggu, Jiangcheng, Gengma, Lvchun, Ning'er, Yuanyang	Hongta, Luquan, Qiubei, Shilin, Tengchong, Jiangchuan, Yuanjiang, Gucheng, Yongping

not been accurately identified. The understanding of the term "wellness" remains at a simple leisure and vacation level, and the importance of the natural environment and cultural environment to health services has not been given due attention. (2) Traditional methods (such as QSM, AHP, FCEM, etc.) are highly subjective, leading to a certain degree of blindness in the identification of WTAs. (3) The development positioning of the WTAs is still not clear, leading to waste of health and wellness resources and unreasonable layout of health and wellness activities. For example, natural WTAs should develop and design health and wellness products based on the pursuit of the true nature of the health and wellness group; comprehensive WTAs can take advantage of regional economic advantages to meet the diversified needs of the health and wellness market. (4) The development model is single, the types of health and wellness products in the health and WTAs are seriously homogenized, and the corresponding industry policies and industry mechanisms have not yet formed institutional norms. (5) The imperfection of social security systems such as pension insurance benefits leads to greater resistance to the continuous development of the health and wellness market, and the potential for the development of the health and wellness industry is difficult to be deeply tapped.

In response to the deficiencies and problems in the current process of identifying health and WTAs (3, 58–60), this study proposes the following suggestions based on the research results, and plans to promote the healthy development of the health

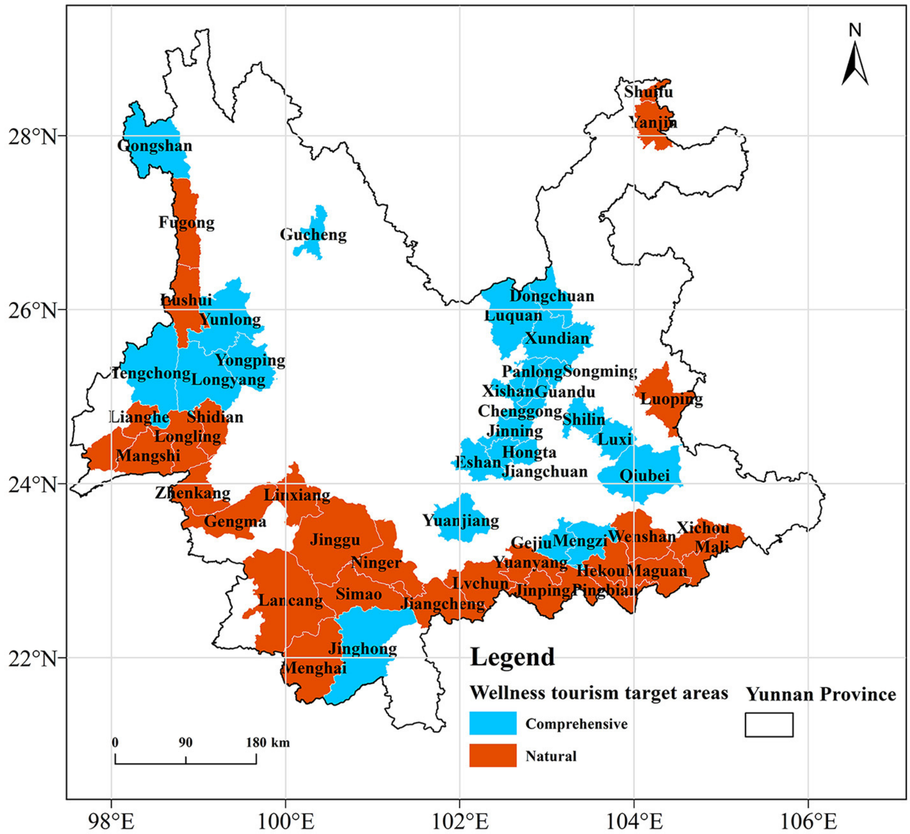

FIGURE 8
Wellness target area classification results.

and wellness industry in a planned and step-by-step manner: (1) It is crucial to fully explore regional health and wellness factors in the early stage of identifying health and WTAs. Developers need to accurately grasp the endowment of regional health and wellness resources, divide different orientation types of health and WTAs according to regional resource advantages, and avoid waste of health and wellness resources. (2) Adopting appropriate identification methods according to local conditions is a prerequisite for the orderly development of health and wellness activities and the reasonable layout of health and WTAs. Developers need to conduct a comprehensive investigation and research on the regional natural environment and socio-economic conditions to minimize the influence of subjectivity on the identification of health and WTAs. (3) High-quality construction standards are a key link in the healthy development of health and WTAs. Local government departments should expedite the establishment and improvement of health and WTAs construction standards, formulate perfect market operation rules, and promote the group and differentiated development of regional health and WTAs to meet the health and wellness needs of different health and wellness groups. (4) The aging population, as the main target group of wellness bases, has a profound influence on the healthy development of WTAs due to their financial capability. Therefore, accelerating the establishment of a multi-level social security system, integrating medical care with older adult care, and promoting the continuous optimization of the pension system framework are essential guarantees for the stable operation of wellness bases.

4.3 Limitations of the study

This study classified and assessed the potential areas suitable for constructing wellness bases (i.e., WTAs) in Yunnan Province, based on the complex interaction between longevity levels and their influencing factors. This provides a scientific basis for the future planning of wellness bases and the healthy development of the wellness industry. However, the study also has some limitations.

On one hand, influenced by factors such as geographical location and political history, the economic development and medical standards of the case study area, Yunnan Province, did not significantly improve until the past decade. This is an important reason why this study only analyzed data from the Seventh National Population Census of 2020. However, this to some extent affected our analysis of the relationship between longevity and geographical environmental factors over a longer time scale, as well as the identification of regional wellness factors. On the other hand, in terms of selecting influencing factors, we did not extensively consider anthropogenic interference factors. How to comprehensively consider more factors, further improve the selection method of evaluation factors, seek a more reasonable way to explore influencing factors, reveal the complex driving processes of factors, perfectly integrate qualitative and quantitative analysis methods, and apply them to the identification of WTAs to more comprehensively understand the complex interactions between geographical phenomena will be the focus of our future research. In subsequent studies, appropriately increasing the evaluation of anthropogenic interference factors (such as local residents' attitudes toward hindering the development of wellness bases, the income levels of the aging population, and the accessibility of WTAs), quantifying qualitative indicators, appropriately expanding the range of influence factor indicators between groups, and considering fuzzy processing of some factor weights to reduce the subjectivity of conclusions may perhaps more effectively improve the scientificity of WTAs identification.

5 Conclusions

Building upon the clarification of the interrelationship between the clustering of longevity populations and the identification of wellness factors, this study associates the selection of wellness bases with longevity levels, proposing a novel approach that considers longevity levels as the primary basis for identifying potential areas for constructing wellness bases (i.e., WTAs). Using Yunnan Province, China, as a typical case study area, the study employs GD and GWR models to explore wellness factors and their modes of action, ultimately delineating WTAs of different types and levels. Compared to traditional methods such as QSM, AHP, and FCEM, this approach can simplify the cumbersome site selection process for WTAs, reduce the influence of researchers' subjective thinking on the results, enhance the scientific rigor of WTAs identification, and provide a more specific and measurable representation for precise site selection of wellness bases in various regions and even globally. Although our study is limited to the analysis of Yunnan Province, China, as a case study area, since we identify WTAs based on longevity phenomena, this method is also applicable to other countries and regions. This will facilitate more scientific and precise site selection for wellness bases, promote the healthy development of the wellness industry, accelerate the improvement of the wellness industry chain, and ultimately contribute to promoting population health and longevity, thereby aiding the global aging process.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YW: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. JW: Data curation, Formal analysis, Investigation, Software, Writing – original draft. XW: Data curation, Formal analysis, Software, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Age and estimated glomerular filtration rate in Chinese older adults: a cohort study from 2014 to 2020

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Objectives: This study aimed to fill the data gap of the course of renal function decline in old age and explore changes in renal function across different health states with increasing age.

Methods: This observational, retrospective, single-center cohort study included 5,112 Chinese older adults (3,321 men and 1,791 women, range 60–104 years). The individual rate of estimated glomerular filtration rate (eGFR) decline was analyzed using linear mixed-effects model to account for repeated measures over the years.

Results: The median age was 66 years, median BMI was 24.56 kg/m^2, and median eGFR was 89.86 mL/min.1.73 m^2. For every 1-year increase in age, women's eGFR decreased by 1.06 mL/min/1.73 m^2 and men's by 0.91 mL/min/1.73 m^2. We observed greater age-related eGFR decline in men and women with high systolic blood pressure (SBP). Men with high triglyceride (TG), high low-density lipoprotein cholesterol (LDL-C), and low high-density lipoprotein cholesterol (HDL-C), had greater age-related eGFR decline. In women, different BMI groups showed significant differences in age-related eGFR decline, with the highest decline in those with obesity. Additionally, participants with normal baseline eGFR had a faster age-related decline than those with low baseline eGFR.

Conclusion: The eGFR declined linearly with age in Chinese older adults, with women exhibiting a slightly faster decline than men. Both men and women should be cautious of SBP. Older adults with normal baseline renal function experienced a faster eGFR decline. Men with high TG, LDL-C, and low HDL-C levels, as well as obese women, should be vigilant in monitoring renal function.

KEYWORDS

aged, glomerular filtration rate, obesity, blood pressure, dyslipidemias

1 Introduction

The global population's aging is the most important medical and social demographic problem worldwide (1). In recent decades, increased average life expectancy has led to a higher proportion of older adults individuals worldwide, accompanied by a rise in non-communicable diseases, including chronic kidney disease (CKD). Aging is a progressive and inevitable biological process, characterized by structural and functional changes in all organs, including the kidneys. The decline in kidney function with advancing age primarily manifests as a decrease in glomerular filtration rate (GFR) (2, 3), the most widely used parameter for measuring kidney function. Although the decrease in GFR with aging has been recognized, the exact estimation of the magnitude of the renal function decline with healthy aging is not yet well-established.

Most studies (4, 5) investigating GFR decline in older adults have relied on cross-sectional designs, which may complicate interpretation due to interindividual modeling across different age groups, disregarding individual trajectories over time.

As the previous study confirmed (6), the generation change in the cross-sectional study and the eGFR decline rate in the longitudinal study are different. Moreover, few studies have included community-dwelling individuals, limiting their ability to reflect real-world decline in a representative older adult population (7). Longitudinal studies with repeated eGFR measurements to model age-related trajectory in old age are scarce. Our research tried to fill the data gap of the course of renal function decline in the older adults population in China, which country has the world's largest older population (8). Gold standard GFR measurement methods, such as inulin clearance or plasma clearance using radiolabeled or non-radiolabeled exogenous markers, are laborious, expensive, and not feasible for routine clinical use (9). Therefore, estimated glomerular filtration rate (eGFR) is a more accessible approach for evaluating kidney function in daily clinical practice.

Considering the frequent comorbidities, such as obesity (10), diabetes (11, 12) and cardiovascular diseases (13), prevalent in the geriatric population and their potential impact on kidney function, we conducted further analyses to examine changes in renal function among the older adults across different health states with increasing age. Investigating the interaction between health status and age on the renal function decline among the older adults is essential for developing targeted interventions that enhance health status and quality of life, promoting healthy aging.

2 Materials and methods

2.1 Study cohort

This study was an observational, retrospective, single-center cohort study, which derived from a total number of 7,871 Chinese older participants who had received a health check at the Health Management Center of Ren Ji hospital in year 2014, with available eGFR information. Participants were followed annually to 2020. After excluding participants with less than 1 follow-up visits (n = 2,759) after 2014, the sample size was 5,112 Chinese older adults (3,321 men and 1,791 women, range 60–104 years), with 22,072 observations (Figure 1). Throughout the study period, the proportion of missing participants in annual follow-up examinations increased progressively, starting from baseline as follows: 0, 18.6, 30.6, 42.2, 51.2, 59.5, 66.1%. Notably, 1,059 participants completed every follow-up throughout the entire cohort study period.

2.2 Estimated glomerular filtration rate

All biochemical tests were performed on venous blood taken after fasting for at least 8 h. The eGFR was calculated by the CKD-EPI equation based on age, sex, and serum creatinine concentration (14). We annually measured serum level of creatinine for each participant through the study (2014–2020).

2.3 Clinical information

Clinical information was abstracted from medical records. In brief, height and body weight were measured by trained nurses. According to body mass index (BMI), participants were classified as underweight (< 18.5 kg/m^2), normal weight (18.5 to 23.9 kg/m^2), overweight (24.0 to 27.9 kg/m^2), or obese (≥ 28.0 kg/m^2) based on Chinese criteria (15). Blood pressure was measured using an automatic blood pressure monitor (HBP-9020, Omron, China) after at least 10-min rest. Venous blood samples were drawn in the morning after participants were fasted for at least 8 h. All the blood samples were analyzed in the same clinical laboratory center. Serum creatinine was analyzed using the enzymatic method by Roche (CREP2; Roche Diagnostics, Mannheim, Germany), fasting blood glucose (FBG) was analyzed using the hexokinase method, total cholesterol (TC) and total triglycerides (TG) were analyzed using the enzymatic colorimetric method, high-density lipoprotein cholesterol (HDL-C) and low-density lipoprotein cholesterol (LDL-C) were analyzed using the homogeneous enzymatic colorimetric assay. These six indicators were analyzed on Roche Cobas C701 module. Hemoglobin was measured by an automatic hematology analyzer (XN-10, Sysmex, Japan). The classified criteria were as follows: systolic blood pressure (SBP) ≥ 140 mmHg (high SBP), diastolic blood pressure (DBP) ≥ 90 mmHg (high DBP) (16), FBG ≥ 7.0 mmoL/L (high FBG) (17), TC ≥ 6.2 mmol/L (high TC), TG ≥ 2.3 mmol/L (high TG), LDL-C ≥ 4.1 mmol/L (high LDL-C), HDL-C < 1.0 mmol/L (low HDL-C) (18), eGFR <60 mL/min/1.73 m^2 (low eGFR). Anemia was diagnosed if hemoglobin was <130 g/L in men while <120 g/L in women (19).

2.4 Statistical analysis

In the descriptive statistics, continuous variables were tested for normal distribution, and if deviating, represented using medians with interquartile ranges (25th-75th quartile). Categorical variables were shown as percentage. The individual rate of eGFR decline (i.e., the

Abbreviations: CKD, Chronic kidney disease; GFR, Glomerular filtration rate; eGFR, Estimated glomerular filtration rate; BMI, Body mass index; FBG, Fasting blood glucose; TC, Total cholesterol; TG, Triglyceride; HDL-C, High-density lipoprotein cholesterol; LDL-C, Low-density lipoprotein cholesterol; SBP, Systolic blood pressure; DBP, Diastolic blood pressure.

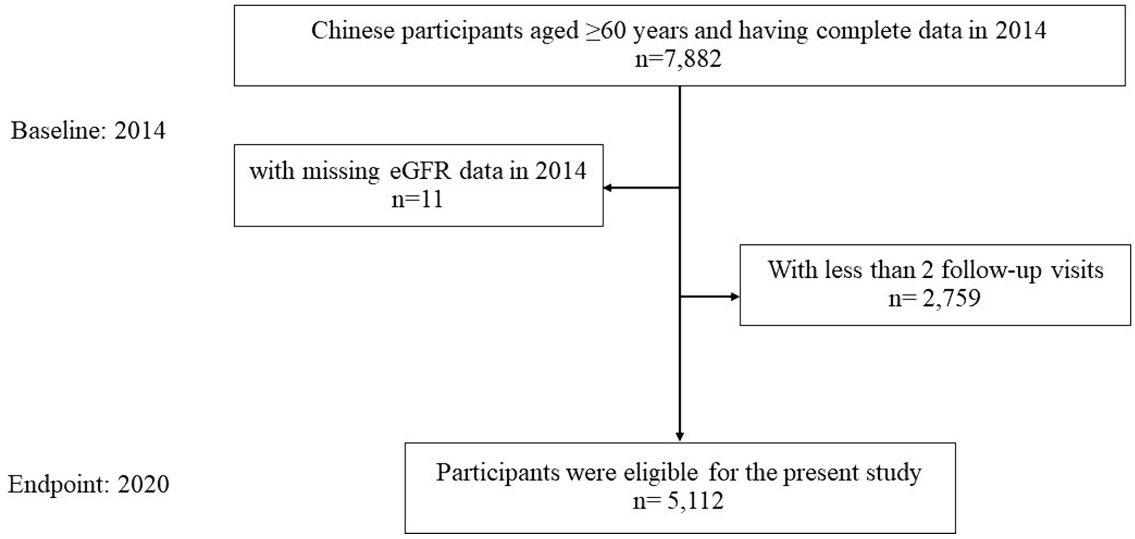

FIGURE 1
Flow chart for participants selection.

slope; ml/min/1.73m^2/year) was analyzed using linear mixed-effects model to account for repeated measures over the years. Missing data were accounted for by using the mixed-effects model (20).

To quantify the age-dependent eGFR, our main analyses tested the association between age and eGFR, while omitting the interaction between age and follow-up time. This was because there was no interaction between age and follow-up duration observed. In contrast, as noticing a significant difference between the sexes, all the analyses were performed among men and women separately (Table 1). We then tested the additive interaction between age and the baseline health status, indicated by other biomarkers on eGFR (Table 2). In the end, sensitivity analyses were conducted to repeat the abovementioned analyses on the 1,059 participants who had undergone all follow-ups, for testing the existence of selection bias.

All statistical analyses were performed with SAS version 9.4 (SAS Institute Inc., Cary, North Carolina). Confidence intervals (CI) were determined at 95% level.

3 Results

3.1 Main baseline characteristics

Among 5,112 participants in 2014, mean eGFR was 87.88 (77.36, 94.43) ml/min/1.73 m2 among men and 92.99 (84.03, 97.46) ml/min/1.73 m^2 among women. The baseline characteristics were presented in Table 3. Baseline characteristics of the study participants showed that men had higher serum creatinine levels, lower eGFR, lower levels of total cholesterol, triglycerides, LDL-C, and HDL-C compared to women. Slightly higher DBP and FBG were observed in males, but no significant difference was found in SBP. The prevalence of underweight and obesity was similar between males and females, but the rate of overweight was higher in males (47.3% versus 38.1%) compared to females.

3.2 Age-related change of eGFR

The slope of age obtained from the linear mixed-effects model represents the change in eGFR for every 1-year increase in age. As shown in Table 1, for every 1-year increase in age, eGFR decreased by 1.06 mL/min/1.73 m^2 (0.99, 1.12) in women, while it decreased by 0.91 mL/min/1.73 m^2 (0.86, 0.95) in men. Specific trajectory according to age groups were presented in Figure 2. We analyzed eGFR decline in healthy older adults without hypertension, hyperglycemia, dyslipidemia, low eGFR, and obesity. In line with the main analysis, the declining trend in the healthy older adults appears to be consistent, albeit at a slower rate of decline (Supplementary Table 1).

3.3 Additive interactions between health indicators and age on eGFR

In Table 2, we observed greater age-related eGFR decline in men and women with high SBP compared to normal SBP (*p interaction* = *0.01* and *0.02*). Men with high TG and high LDL-C also had greater age-related eGFR decline compared to normal TG and LDL-C (both *p interaction* < *0.001*). Additionally, men with low HDL-C had larger age-related eGFR decline compared to normal HDL-C (*p interaction* = *0.006*). In women, there was a significant difference in the age-related decline of eGFR among different BMI groups, with the highest decline observed in obese women and the slowest decline observed in women with normal weight (*p interaction* = *0.01*). Furthermore, there was no significant difference in age-related decline of eGFR between anemic individuals, irrespective of gender, and non-anemic individuals. In both men and women with normal baseline eGFR, the age-related decline was significantly faster than in those with low baseline eGFR.

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TABLE 1 Age-related change of eGFR (ml/min/1.73 m^2) in 5,112 Chinese older adults during the whole cohort study.

Sex	2014 (baseline)	2015	2016	2017	2018	2019	2020	Slope $_{age}$
Men (n = 3,321)	Ref	−1.06 (−1.33, −0.80)	−4.87 (−5.16, −4.57)	−2.21 (−2.55, −1.86)	−3.00 (−3.42, −2.59)	−3.08 (−3.54, −2.62)	−3.80 (−4.34, −3.26)	−0.91 (−0.95, −0.86)
Women (n = 1,791)	Ref	−2.01 (−2.37, −1.65)	−6.52 (−6.96, −6.07)	−3.20 (−3.64, −2.76)	−4.34 (−4.85, −3.83)	−4.19 (−4.80, −3.59)	−5.07 (−5.78, −4.37)	−1.06 (−1.12, −0.99)

The data was analyzed by linear mixed-effects model with random intercept. The data under each natural year displayed the change value of mean eGFR (95% confidence interval) in that year compared with the baseline. The last column Slope $_{age}$ represented the slope of eGFR decline during the whole study period fitted by the linear mixed-effects model, with age measured in years.

3.4 Sensitivity analyses

The sensitivity analysis of 1,059 participants who completed every follow-up revealed that estimated values in Supplementary Table 2 closely mirrored those in the main analyses. Confidence intervals in Supplementary Table 3 consistently overlapped with the main analyses. Discrepancies in p-values across certain groups may be attributed to varying sample sizes, with selection bias less likely to influence outcomes.

4 Discussion

We investigated the course of kidney function decline in the cohort of older participants using repeat GFR estimates and observed the following main findings. First, we found that the eGFR, determined by serum creatinine, declined linearly with age in Chinese older adults. For every 1-year increase in age, eGFR decreased by 1.06 mL/min/1.73 m^2 (0.99, 1.12) in women, while it decreased by 0.91 mL/min/1.73 m^2 (0.86, 0.95) in men.

The discovery of linear decline was like the longitudinal German population-based cohort in persons aged 70 and above with a repeated estimation of GFR over a median of 6.1 years of follow-up (7). The possible reason is that aging leads to notable kidney structural and functional changes, even without age-related health issues. Kidney cortical volume decreases, surface roughness increases, and simple renal cysts grow with age. Additionally, histologic signs of nephrosclerosis increase with age, as does the decline in nephron number and whole-kidney GFR (21). Moreover, a recent longitudinal analysis of older adults stage 4 and 5 CKD showed similar linear decline, but opposite gender differences compared to our study (22). This difference may be due to higher comorbidity burden and sex differences in advanced CKD patients. For instance, male participants had twice the myocardial infarction rate of female participants. One of the possible reasons for the gender difference may be caused by a sex-dependent decrease in muscle mass with age, biasing our eGFRs.

Second, we found that older adults individuals with poor baseline renal function experienced a slower decline in age-related glomerular filtration rate compared to those with normal renal function. A large Japanese longitudinal study revealed for the first time that eGFR decline rate in healthy subjects depended mainly on eGFR at baseline, but not on age (6). The results of this study supported our findings, which were different from those of previous studies. For example, a study more than 10 years ago showed that eGFR decline was faster with a lower baseline eGFR (23). The discrepancy in research findings was primarily attributed to the previous study measuring serum creatinine only twice over a ten-year period, while our study conducted annual measurements for 6 years. Furthermore, distinct fitting models were utilized for statistical analysis. The reason why the rate of eGFR decline was slower with a lower baseline eGFR is unclear, but a compensatory mechanism might work as kidney function decreases.

Furthermore, we observed greater age-related eGFR decline both in men and women with high SBP compared to normal SBP. A Japanese cohort study also showed that a difference in SBP, but not DBP, is independently associated with a rapid eGFR decline in the general Japanese population, including older subjects (24). Various

TABLE 2 Additive interactions between baseline health indicators and age on eGFR among 5,112 Chinese older adults.

Stratified variables	Men (n = 3,321)			Women (n = 1,791)		
	N	Beta-estimate for slope	p for interaction	N	Beta-estimate for slope	p for interaction
High SBP	1,386	−0.95 (−1.01, −0.89)	0.01	761	−1.13 (−1.22, −1.05)	0.02
Normal SBP	1834	−0.85 (−0.91, −0.79)		923	−1.00 (−1.09, −0.92)	
High DBP	603	−0.97 (−1.06, −0.87)	0.16	185	−1.08 (−1.26, −0.91)	0.82
Normal DBP	2,617	−0.90 (−0.95, −0.85)		1,499	−1.06 (−1.13, −0.99)	
Underweight	74	−0.67 (−0.91, −0.42)	0.24	34	−1.00 (−1.36, −0.63)	0.01
Normal weight	1,103	−0.90 (−0.97, −0.84)		732	−0.96 (−1.05, −0.87)	
Overweight	1,401	−0.92 (−0.98, −0.85)		607	−1.08 (−1.18, −0.97)	
Obesity	384	−0.93 (−1.05, −0.81)		220	−1.26 (−1.41, −1.10)	
High FBG	368	−0.91 (−1.03, −0.80)	0.88	170	−1.14 (−1.30, −0.97)	0.34
Normal FBG	2,952	−0.90 (−0.95, −0.86)		1,621	−1.06 (−1.12, −0.99)	
High TC	227	−1.05 (−1.21, −0.90)	0.06	342	−1.08 (−1.20, −0.95)	0.64
Normal TC	2,796	−0.90 (−0.95, −0.85)		1,390	−1.05 (−1.12, −0.97)	
High TG	493	−1.08 (−1.18, −0.97)	< 0.001	297	−1.11 (−1.24, −0.98)	0.32
Normal TG	2,828	−0.89 (−0.94, −0.84)		1,494	−1.04 (−1.11, −0.98)	
High LDL-C	197	−1.20 (−1.37, −1.04)	< 0.001	250	−1.03 (−1.18, −0.89)	0.73
Normal LDL-C	3,098	−0.89 (−0.94, −0.84)		1,526	−1.06 (−1.13, −0.99)	
High HDL-C	540	−1.03 (−1.13, −0.93)	0.008	106	−1.08 (−1.28, −0.88)	0.78
Normal HDL-C	2,755	−0.89 (−0.94, −0.84)		1,671	−1.05 (−1.12, −0.98)	
Anemia	209	−0.84 (−0.98, −0.70)	0.77	106	−1.17 (−1.35, −0.99)	0.11
Non-anemia	3,110	−0.86 (−0.91, −0.81)		1,684	−1.02 (−1.08, −0.95)	
Low eGFR	191	−0.14 (−0.27, −0.005)	< 0.001	59	0.04 (−0.20, 0.28)	< 0.001
Normal eGFR	3,130	−0.70 (−0.74, −0.66)		1732	−0.85 (−0.91, −0.79)	

High SBP: systolic blood pressure ≥ 140 mmHg. High DBP: diastolic blood pressure ≥ 90 mmHg. High TC: total cholesterol ≥ 6.2 mmol/L. High TG: triglyceride ≥ 2.3 mmol/L. High LDL-C: low-density lipoprotein cholesterol ≥ 4.1 mmol/L. Low HDL-C: high-density lipoprotein cholesterol < 1.0 mmol/L. Low eGFR: estimated glomerular filtration rate < 60 mL/min/1.73 m^2. Participants were classified into four BMI groups: underweight (BMI < 18.5 kg/m^2), normal weight (18.5 kg/m^2 ≤ BMI < 24 kg/m^2), overweight (24 kg/m^2 ≤ BMI < 28 kg/m^2), and obesity (BMI ≥ 28 kg/m^2). High FBG: fasting blood glucose ≥ 7.0 mmol/L.Anemia in men: hemoglobin < 130 g/L; women: hemoglobin < 120 g/L. The data were analyzed by linear mixed-effects model with random intercept.

TABLE 3 Baseline characteristics of 5,112 Chinese older adults.

Characteristics	Total (n = 5,112)	Men (n = 3,321)	Women (n = 1,791)	p value
Age (years)	66 (62, 73)	66 (62, 74)	65 (62, 72)	< 0.001
BMI (kg/m^2)	24.56 (22.48, 26.53)	24.69 (22.68, 26.57)	24.14 (22.13, 26.45)	< 0.001
SBP (mmHg)	137 (124, 149)	136 (124, 148)	137 (124, 150)	0.40
DBP (mmHg)	79 (71, 86)	77.2 (69.2, 86.8)	76 (68, 83)	< 0.001
Creatinine (μmol/L)	70.6 (60.0, 81.9)	76.2 (68.6, 84.9)	57.2 (51.1, 64.0)	< 0.001
eGFR (ml/min/1.73 m^2)	89.86 (79.73, 95.68)	87.88 (77.36, 94.43)	92.99 (84.03, 97.46)	< 0.001
TC (mmol/L)	5.06 (4.44, 5.71)	4.87 (4.26, 5.48)	5.39 (4.81, 6.05)	< 0.001
TG (mmol/L)	1.33 (0.97, 1.90)	1.31 (0.95, 1.88)	1.35 (1.01, 1.94)	0.003
LDL-C (mmol/L)	2.99 (2.46, 3.51)	2.88 (2.36, 3.41)	3.17 (2.67, 3.74)	< 0.001
HDL-C (mmol/L)	1.32 (1.12, 1.58)	1.25 (1.06, 1.49)	1.47 (1.25, 1.72)	< 0.001
FBG (mmol/L)	5.33 (4.96, 5.90)	5.40 (5.00, 5.99)	5.30 (4.90, 5.84)	< 0.001
Hemoglobin (g/L)	144 (134, 154)	150 (142, 158)	134 (128, 140)	< 0.001
Underweight (n)	2.37% (108)	2.50% (74)	2.13% (34)	0.44
Overweight (n)	44.08% (2,008)	47.30% (1,401)	38.10% (607)	< 0.001
Obesity (n)	13.26% (604)	12.96% (384)	13.81% (220)	0.42

BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; eGFR, estimated glomerular filtration rate; FBG, fasting blood glucose; TC, total cholesterol; TG, triglyceride; LDL-C, low-density lipoprotein cholesterol; HDL-C, high-density lipoprotein cholesterol. The difference between men and women was tested by Wilcoxon text. Variables were presented as medians with interquartile ranges (25th–75th percentile).

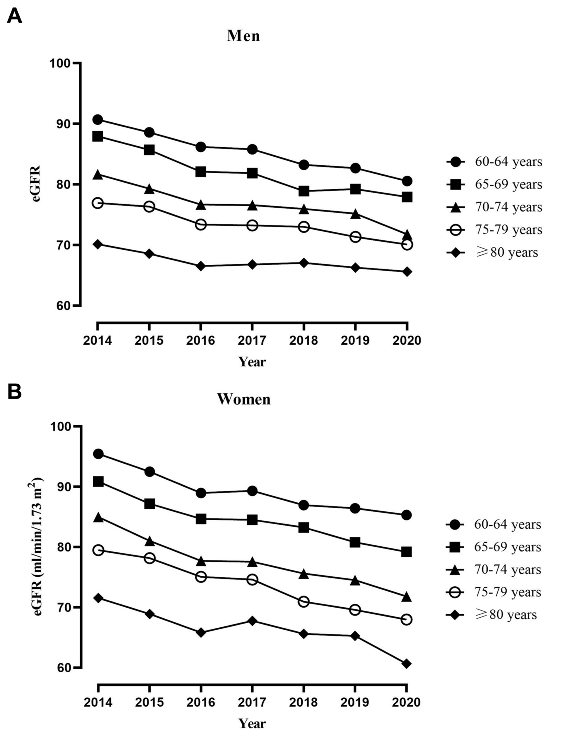

FIGURE 2
Trajectory of average eGFR in different age groups of older adults individuals throughout the study period. **(A)** Trajectory of average eGFR in 3,321 men. **(B)** Trajectory of average eGFR in 1,791 women.

mechanisms might contribute to kidney injuries in older adults hypertensive patients, including the renin-angiotensin-aldosterone system, oxidative stress, endothelial dysfunction, and genetic and epigenetic factors (25).

Finally, we observed that men with high triglyceride, high LDL-C, or low HDL-C had a faster age-related eGFR decline. Additionally, in BMI groups, obese women experienced the fastest age-related eGFR decline. Other studies (26, 27) also found that high triglyceride and low HDL-C predicted renal function decline. A 7-year cohort study of the older adults found that baseline BMI was associated with an increased risk of rapid eGFR loss (28). Pathways through which obesity might cause renal damage were not well understood. Potential mechanisms included sympathetic nervous and renin-angiotensin-aldosterone systems activation, mechanical stress, hormonal imbalance, and production of inflammatory cytokines (29). Some scholars proposed that renal lipid accumulation could cause structural and functional changes in mesangial cells, podocytes, and proximal tubule cells, affecting nephron function (30). Irrespective of the underlying pathophysiological mechanisms, it was crucial for older adults with obesity or hyperlipidemia to closely monitor their renal function. Further research and clinical trials were needed to assess the efficacy of these interventions in this vulnerable population.

The study's longitudinal design with a large cohort and multiple biomarkers enhances its uniqueness. It improves our understanding of age-related kidney function decline and provides valuable insights into eGFR decline patterns in old age. It addresses the data gap on renal function decline in China's older adults population across different health conditions. This study has practical implications for clinical practice and future gerontology research, facilitating the development of targeted interventions to enhance the health status and quality of life of the older adults, promoting healthy aging.

Our study did not include the endogenous biomarker cystatin C, which is potentially more suitable for assessing renal function in older individuals compared to creatinine, as creatinine levels can be affected by sarcopenia (31). This retrospective observational study may include both healthy and sick individuals. Limited data on proteinuria (24), etiological diagnosis of CKD, comorbidities (10, 12, 13), and medication (32) makes it impossible to exclude the impact of diseases and medication on renal function. These uncontrolled confounding factors restrict the generalizability of the study results. Additionally, there may be other factors, such as socioeconomic status (33), dietary habits (34, 35), and physical activity (36), that could influence the risk of renal function decline. However, information regarding these factors was not available in our study.

5 Conclusion

The eGFR, determined by serum creatinine, declined linearly with age in Chinese older adults. Women exhibited a slightly faster age-related decline in eGFR compared to men. Additionally, older adults with good baseline renal function experienced a more rapid eGFR decline than those with lower baseline eGFR. Both men and women should be cautious of SBP. Men with high TG, LDL-C, and low HDL-C levels, as well as obese women, should be vigilant in monitoring renal function.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethical Committee of Ren Ji Hospital. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

YJ: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. QC: Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Data curation. WH: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. TX: Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. MT: Writing – original draft, Visualization, Software, Methodology, Data curation. YL: Writing – review & editing, Visualization, Supervision, Conceptualization. RX: Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Regular exercise reduces the risk of all-cause mortality in socially isolated older adults: the Otassha Study

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Introduction: Social isolation is associated with increased mortality risk. On the other hand, some older adults prefer to be alone. Additionally, predictors of isolation are mostly unchanged across interventions. Therefore, knowledge of how to prevent negative health outcomes in isolation would be beneficial. One of the factors that reduces the risk of mortality is regular exercise. However, to date, no studies to our knowledge have examined whether regular exercise reduces mortality among socially isolated individuals. This study aimed to determine the effects of the combination of social isolation and regular exercise on mortality among community-dwelling older adults.

Methods: This prospective cohort study was part of the larger Otassha Study of community-dwelling older adults living in Itabashi Ward, Tokyo, Japan. In October 2012, 835 individuals (males = 350, females = 485; mean age 73.1 years) completed a comprehensive baseline health survey. Individuals were considered socially isolated if their frequency of interactions with others averaged less than once per week. Regular exercise was defined as exercise performed at least twice a week. The participants were assigned to one of the following four groups: (1) not isolated with regular exercise, (2) not isolated without regular exercise, (3) isolated with regular exercise, and (4) isolated without regular exercise. All-cause mortality information was obtained from the ward office database. Follow-ups were conducted until 1 November 2020. A Cox proportional regression analysis was performed.

Results: A final analysis was performed on a complete dataset of 735 participants (males = 303, females = 432; mean age 72.9 years). A total of 132 (18.0%), 426 (58.0%), 27 (3.7%), and 150 (20.4%) participants were assigned to groups 1, 2, 3, and 4, respectively. The mortality rates in groups 1, 2, 3, and 4 were 6.1%, 9.2%, 7.4%, and 19.3%, respectively. Compared with group 1, isolated individuals who did not perform regular exercise had a significantly higher mortality rate [adjusted hazard ratio (aHR), 2.48; 95% confidence interval (CI), 1.12–5.52]. However, no significant association was noted in isolated individuals who performed regular exercise (aHR, 1.25; 95% CI, 0.26–5.91).

Conclusion: Regular exercise was associated with a decrease in mortality risk, regardless of social isolation status. Thus, our results indicate that encouraging isolated older adults to exercise regularly may reduce their negative health outcomes.

KEYWORDS
social isolation, exercise, all-cause mortality, older adults, cohort study

1 Introduction

Social isolation is one of the most serious problems faced by aging societies. According to the World Health Organization, social isolation is related to a lack of contact with family, friends, and others (1). The estimated prevalence of social isolation among older adults is as high as 88%, depending on the definition of isolation (2). Social isolation in old age leads to various negative health outcomes, such as anxiety and depression (3), poor sleep quality (4), disability (5), and dementia (6). One particular concern is that social isolation increases mortality rates (7, 8). A previous study reported that social isolation has a greater effect on mortality than established risk factors, such as smoking, alcohol consumption, and physical inactivity (9). Additionally, socially isolated individuals have higher suicide rates (10). Consequently, it is important to encourage older adults to maintain interactions with others and avoid the risk of social isolation.

However, the number of other individuals with whom older adults can interact decreases with age. As individuals age, their number of friends, relatives, and other social connections decreases (11), and the death of peers limits their social interactions (8). Moreover, some older adults prefer to be alone (12). A previous study revealed that solitude-seeking has more positive ramifications for older adults (13). In this case, in addition to preventing social isolation, there is a need to examine ways to maintain health even when isolated. However, evidence from this perspective is limited. Additionally, predictors of isolation, such as sex, age, and economic status, are mostly unchanged across interventions (2). Therefore, knowledge of how to prevent negative health outcomes in isolation would be beneficial.

Exercise is a lifestyle habit that reduces mortality risk. It improves physical function and quality of life, prevents frailty and sarcopenia, reduces noncommunicable chronic diseases, and reduces all-cause and cause-specific mortality, such as cardiovascular disease and cancer (14–17). Physical inactivity and sedentary behavior increase the risk of depression and all-cause and cardiovascular mortality among older adults (18, 19). Furthermore, exercise is beneficial for diseases common among older adults. Regular exercise can have anti-atherogenic effects on the vasculature, independent of its effects on traditional cardiovascular disease risk factors (20). Additionally, exercise interventions are beneficial for glycemic control and cardiovascular risk factors associated with diabetes (21). Exercise may thus reduce mortality via these mechanisms. However, to date, no studies to our knowledge have examined whether regular exercise reduces mortality, even among socially isolated individuals at a high risk of death.

Therefore, we aimed to ascertain whether regular exercise reduces the risk of mortality among socially isolated older adults living in the community. To address this question, this study aimed to determine the effects of the combination of social isolation and regular exercise on mortality among community-dwelling older adults.

2 Materials and methods

2.1 Participants

This study was part of "the Otassha Study" on community-dwelling older adults living in Itabashi Ward, an urban area in Tokyo, Japan. The Otassha Study began in October 2011 and involves ongoing annual health checkups. At the beginning of the study, we sent a mail recruitment letter to all residents aged 65–84 years who were registered in the Basic Resident Register, excluding institutionalized residents and participants from previous surveys conducted by our institute ($N = 7{,}015$). In 2011, 913 older adults participated in the health checkup. The health checkups included motor and cognitive functioning tests, medical interviews, and a questionnaire on daily life, such as lifestyle habits, social interactions, and emotions. We followed up with our participants via the annual health checkups, and new participants were recruited on an annual basis as they turned 65 years of age. The details of this cohort have been described previously (22). In this study, we used data obtained in 2012 as the baseline survey. The protocol was the same annually; however, the measures varied. As social isolation was assessed for the first time in 2012, the baseline for this study was set to 2012. The sample consisted of 835 individuals (males = 350, females = 485; mean age 73.1 years). The study was conducted in October 2012. Data were collected through the comprehensive health survey.

Ethical approval was granted by the Ethics Committee of the Tokyo Metropolitan Institute for Geriatrics and Gerontology (approval no.: E-35, 2012). Prior to this study, all the participants provided written informed consent. This study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2 Measures

2.2.1 Social isolation

Social isolation was defined based on the frequency of face-to-face and non-face-to-face contact (talking on the phone or via e-mail or letter) with nonresident families and friends (23, 24). The questionnaire we utilized is widely used to assess social isolation and has been reported to be associated with mortality among older adults (23). The participants were considered socially isolated if their frequency of interaction with others averaged less than once per week (23, 24).

2.2.2 Regular exercise

Regular exercise was defined according to weekly exercise frequency based on a nationwide Japanese survey, the National Health and Nutrition Survey (25). Exercising twice or more a week was considered regular exercise, as it has been found that exercising at least twice a week is necessary to improve physical fitness (26).

TABLE 1 Characteristics of the participants based on social isolation and exercise status ($n = 735$).

	Not isolated with regular exercise ($n = 132$)		Not isolated without regular exercise ($n = 426$)		Isolated with regular exercise ($n = 27$)		Isolated without regular exercise ($n = 150$)	
	n	%	*n*	%	*n*	%	*n*	%
Sex								
Male	42	31.8%	162	38.0%	14	51.9%	85	56.7%
Female	90	68.2%	264	62.0%	13	48.1%	65	43.3%
Age (mean [SD])	72.0	(4.6)	73.1	(5.1)	71.6	(4.9)	73.4	(5.3)
Chronic diseases								
0	74	56.1%	209	49.1%	17	63.0%	55	36.7%
>1	58	43.9%	217	50.9%	10	37.0%	95	63.3%
IADLs disability (mean [SD])	0.1	(0.3)	0.1	(0.4)	0.1	(0.5)	0.2	(0.7)
Follow-up month (mean [SD])	92.8	(14.3)	92.1	(13.9)	89.3	(22.8)	84.8	(23.2)
Follow-up status								
Survived	117	88.6%	361	84.7%	23	85.2%	106	70.7%
Died	8	6.1%	39	9.2%	2	7.4%	29	19.3%
Censored[a]	7	5.3%	26	6.1%	2	7.4%	15	10.0%

[a]Censored participants include those who moved away and refused to respond to the survey during the follow-up period. IADLs, instrumental activities of daily living; SD, standard deviation.

2.2.3 All-cause mortality

All-cause mortality information was obtained from 1 October 2012 to 1 November 2020, from the database administered by the ward office. This mortality information was provided through the notification of death forms for residents.

2.2.4 Covariates

Sex, age, chronic diseases, and disability in instrumental activities of daily living (IADLs) were assessed as covariates. A nurse assessed whether the participants were currently being treated for one or more of five chronic diseases: hypertension, stroke, heart disease, diabetes, and cancer. We assessed IADLs using a subscale of the Tokyo Metropolitan Institute of Gerontology Index of Competence, which includes five questions on instrumental self-maintenance (27). The total number of answers concerning what the participants were unable to perform was used as the IADLs disability score (ranging from 0 [no disability] to 5).

2.3 Statistical analyses

Considering social isolation and regular exercise status, the participants were assigned to one of the following four groups: (1) not isolated with regular exercise, (2) not isolated without regular exercise, (3) isolated with regular exercise, and (4) isolated without regular exercise. Data on participant characteristics are presented as means and standard deviations (SDs) for continuous variables and as numbers and percentages for categorical variables.

The relationship between the combination of social isolation and regular exercise and mortality was examined using a Cox regression model with isolation and exercise (reference: not isolated with regular exercise) as independent variables. We fitted the crude and adjusted models, which were adjusted for sex, age, chronic diseases, and IADLs disability in 2012. To assess the possibility of reverse causality, participants who died during the first year were excluded from sensitivity analysis.

All statistical analyses were performed using IBM SPSS Statistics for Windows, version 27 (IBM Japan, Ltd., Tokyo, Japan). Statistical significance was set at $p < 0.05$.

3 Results

After excluding 100 participants with missing data, a final analysis was performed on the complete datasets available for 735 participants (males = 303, females = 432; mean age [SD], 72.9 [5.1] years). In total, 132 (18.0%), 426 (58.0%), 27 (3.7%), and 150 (20.4%) participants were assigned to group 1 (not isolated with regular exercise), group 2 (not isolated without regular exercise), group 3 (isolated with regular exercise), and group 4 (isolated without regular exercise), respectively. The baseline characteristics of the patients are shown in Table 1. Isolated participants were more likely to be male. Participants who did not exercise regularly were slightly older than those who exercised regularly. The mortality rates in groups 1, 2, 3, and 4 were 6.1%, 9.2%, 7.4%, and 19.3%, respectively.

In the crude model, isolated individuals who did not exercise regularly had a significantly higher mortality rate [hazard ratio (HR), 3.62; 95% confidence interval (CI), 1.66–7.93] compared with those who were not isolated but did exercise regularly (Table 2). However, no significant association was noted in isolated individuals who exercised regularly (HR, 1.27; 95% CI, 0.27–5.98). In the adjusted model, only isolated participants without regular exercise showed a significantly increased mortality rate (HR, 2.48; 95% CI, 1.12–5.52). No significant association was noted in isolated participants who

TABLE 2 Association between social isolation and exercise status and mortality (n = 735).

	n	Death	Incidence per 1,000 person-years	Crude HR (95% CI)	Adjusted HR (95% CI)
Not isolated with regular exercise	132	8	7.84	Reference	Reference
Not isolated without regular exercise	426	39	11.93	1.53 (0.71–3.28)	1.28 (0.60–2.75)
Isolated with regular exercise	27	2	9.95	1.27 (0.27–5.98)	1.25 (0.26–5.91)
Isolated without regular exercise	150	29	27.36	3.62 (1.66–7.93)	2.48 (1.12–5.52)

Adjusted for sex, age, instrumental activities of daily living, and chronic diseases. CI, confidence interval, HR, hazard ratio.

TABLE 3 Association between social isolation and exercise status and mortality after excluding older adults who died during the first 1 year of follow-up (n = 733).

	n	Death	Incidence per 1,000 person-years	Crude HR (95% CI)	Adjusted HR (95% CI)
Not isolated with regular exercise	131	7	6.87	Reference	Reference
Not isolated without regular exercise	426	39	11.93	1.75 (0.78–3.92)	1.47 (0.66–3.29)
Isolated with regular exercise	27	2	9.95	1.45 (0.30–7.00)	1.43 (0.29–6.91)
Isolated without regular exercise	149	28	26.42	4.01 (1.75–9.19)	2.73 (1.17–6.36)

Adjusted for sex, age, instrumental activities of daily living, and chronic diseases. CI, confidence interval, HR, hazard ratio.

exercised regularly (HR, 1.25; 95% CI, 0.26–5.91). After excluding older adults who died during the first year, only isolated participants without regular exercise showed a significantly increased mortality rate (HR, 2.73; 95% CI, 1.17–6.36) in the adjusted model (Table 3).

4 Discussion

This study examined the effects of the combination of social isolation, which increases mortality, and regular exercise, which decreases mortality. The results showed that, compared with participants who were not isolated and did engage in regular exercise, those who were isolated without regular exercise had a higher risk of mortality, whereas those who were isolated but engaged in regular exercise did not have an increased risk of mortality. Therefore, our study indicates that regular exercise reduces the risk of mortality among socially isolated older adults living in the community.

This study revealed that regular exercise had a positive effect on mortality risk, even in isolated individuals. This result is consistent with evidence from previous studies showing that exercise reduces mortality (16, 17). In particular, isolated individuals are at a higher risk of cardiovascular disease and death from cardiovascular disease than non-isolated individuals (28–30). It is possible that death from cardiovascular disease was reduced in our study, even in isolated older adults, because exercise can have anti-atherogenic effects on the vasculature (20) and improve cardiovascular disease (15). However, we cannot speculate on these relationships because no analysis was performed on the cause of death in this study owing to the limited sample size. Future analyses based on the cause of death will further clarify the relationship between social isolation, regular exercise, and mortality.

The prevalence of social isolation in this study was approximately 25%, similar to that previously reported for older adults in Japan (31). Preventing social isolation in old age is crucial because isolation leads to negative health outcomes, including death (7, 8). However, if the negative effects of isolation can be eliminated, we may be able to achieve a society that accepts an individual's preference for isolation. The findings of this study may help improve the health of older adults who willingly isolate themselves. Furthermore, future analyses that consider socializing preferences may deepen our understanding of this area.

This study showed that promoting regular exercise in isolated older adults may be beneficial; however, the percentage of those who engaged in regular exercise was low (15.6%) compared with that of non-isolated older adults (23.7%). Healthy lifestyle habits, such as physical activity, increase with social connectedness (32, 33); those who are isolated may be less likely to develop exercise habits through social connectedness. Although network interventions or opinion leaders are effective in promoting healthy lifestyle habits, such as physical activity (34, 35), these interventions are likely to be ineffective for isolated individuals with few social connections. However, a previous review on the determinants of exercise reported insufficient evidence (36); thus, further investigations are required to determine how to promote the acquisition of exercise habits among socially isolated older adults. The following methods should be considered to promote regular exercise among isolated individuals. First, isolated older adults who exercise should be surveyed to determine the type of exercise they practice, and the types of exercise that are easy to practice in isolation should be promoted. For example, since ball sports require a partner, isolated older adults can practice walking, strength training, and swimming instead, as they can be practiced alone. Second, a mobile phone-based intervention may be beneficial because older adults who do not like socializing may not participate in face-to-face, classroom-type exercise classes. Indeed, the World Health Organization recommends the promotion of physical activity using digital technology for older adults (37).

4.1 Limitations

This study had some limitations. First, regular exercise was examined only in terms of frequency, not intensity, type, or duration. Second, owing to the small number of isolated participants who exercised regularly, we did not sufficiently adjust for other factors related to mortality, such as self-rated health and depression. A stratification analysis by sex could not be performed for the same reason. Third, since there is no standardized scale for assessing social isolation, this study possibly included only one aspect of social isolation in the analysis. Finally, as this study targeted older adults living in one area of Japan, caution should be exercised in generalizing the findings to other areas. However, to our knowledge, this is the first study to show that, even among isolated older adults, engaging in regular exercise positively affected mortality, which is highly significant in today's aging society.

4.2 Conclusion and implications

Regular exercise was associated with a decrease in mortality risk, regardless of social isolation status. Therefore, our results indicate that encouraging isolated older adults to exercise regularly may reduce their negative health outcomes. Further research is required on ways to maintain health even in isolation to achieve a society that allows for a diversity of socializing preferences among older adults.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Ethics Committee of the Tokyo Metropolitan Institute for Geriatrics and Gerontology. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

ME: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft. HK: Conceptualization, Investigation, Writing – original draft. KIm: Conceptualization, Investigation, Writing – original draft. YF: Investigation, Writing – review & editing. KIh: Investigation, Writing – review & editing. HH: Investigation, Writing – review & editing. SO: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Trajectories and influencing factors of cognitive function and physical disability in Chinese older people

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Introduction: Dementia and physical disability are serious problems faced by the aging population, and their occurrence and development interact.

Methods: Based on data from a national cohort of Chinese people aged 60 years and above from the China Health and Retirement Longitudinal Survey from 2011 to 2018, we applied the group-based trajectory model to identify the heterogeneous trajectories of cognitive function and physical disability in participants with different physical disability levels. Next, multinomial logistic regression models were used to explore the factors affecting these trajectories.

Results: The cognitive function trajectories of the Chinese older people could be divided into three characteristic groups: those who maintained the highest baseline level of cognitive function, those with a moderate baseline cognitive function and dramatic progression, and those with the worst baseline cognitive function and rapid–slow–rapid progression. The disability trajectories also fell into three characteristic groups: a consistently low baseline disability level, a low initial disability level with rapid development, and a high baseline disability level with rapid development. Compared with those free of physical disability at baseline, a greater proportion of participants who had physical disability at baseline experienced rapid cognitive deterioration. Education, income, type of medical insurance, gender, and marital status were instrumental in the progression of disability and cognitive decline in the participants.

Discussion: We suggest that the Chinese government, focusing on the central and western regions and rural areas, should develop education for the older people and increase their level of economic security to slow the rate of cognitive decline and disability among this age group. These could become important measures to cope with population aging.

KEYWORDS

disability, cognitive function, aging, development trajectory, influencing factors

Introduction

Global aging is increasing, with one sixth of the world's population being over the age of 60 in 2023 (1). Several studies have shown that the prevalence of dementia and physical disability in the older people increases with age (2, 3). The number of people with dementia worldwide is expected to increase from 57.4 million in 2019 to 152.8 million in 2050 (4). In China, there were approximately 16.25 million people with dementia in 2020, and that number is expected to approximately triple to 48.98 million by 2050 (5). Notably, the proportion of older people with disabilities among the total number of persons with disabilities in China is projected to exceed 57% in 2030, and will further increase to over 70% by 2050 if no preventive or control measures are taken (6). Meanwhile, increased longevity has led to a sustained increase in the number of years lived with physical disability, which has in turn increased the financial burden in later life for both disabled individuals and society (7, 8). Cognitive function and physical disability present major challenges to healthy aging today (9). Understanding the progression of cognitive degeneration and physical disability can contribute to the formulation of preventive or control measures.

During the progression from normal cognition to dementia, there is an intermediate stage of 'mild cognitive impairment' (10), which does not necessarily get progressively worse and may be reversible, according to previous research (11, 12). Existing studies have explored the trajectory of cognitive degeneration in the older people, but their findings on the typology of these trajectories have been inconsistent. Some studies, including three in China, have reported between three and six trajectories of cognitive degeneration among the older people (13–24). Specifically, some studies in the United States (US), the United Kingdom (UK), Japan, and China have shown that the higher the baseline cognitive level of older people, the slower their future decline in cognitive function. However, two other studies in China found that the older population with the most stable maintenance of cognitive function comprised people with a moderate baseline cognitive function (19, 20).

There is similar variation in studies on the trajectories of physical disability in the older people. Regarding the progression of mobility degeneration, the existence of a reversible trajectory among older adults has only been supported by two studies, both conducted in the Netherlands (25, 26). Nusselder et al. identified two groups of Dutch persons aged 15–74 years with reversible trajectories (26). One group was characterized by initial mild disability and gradual functional improvement, while those in the other group were moderately disabled at baseline with partial recovery in the subsequent months. In Gardeniers et al., the recovery of physical function was observed only among Dutch men aged 75 years and above, not their female counterparts (25). Some studies have identified between three and nine trajectories of physical disability in the older people (26, 27). Additionally, many researchers in the UK, the US, the Netherlands, and China have identified two groups with opposite patterns of mobility degeneration: those suffering the severest disability in the beginning, progressing most rapidly and reaching the worst status during the follow-up period; and those with no or little disability initially, then persistent low levels of physical disability over a period of years (25, 28–30). However, another study in China in 2015 showed that older people with a low level of disability (1 item of disability) at baseline later experienced the highest level of disability (nearly 10 items of disability) due to the rapid progression of their disability over the following decade (31).

Most previous studies have focused on the progression of physical disability and cognitive function separately. However, it has been shown that the two mutually affect each other (32, 33) and that there is a possibility of co-morbidity (34). Therefore, it is relevant to study the covarying trajectory of cognitive function and disability. At present, only five studies, all conducted in the US, have studied both cognitive function and physical disability, and they have found that the trajectories of disability vary with the state of cognitive function (27, 35–38). For example, a 2016 study by Tolea et al. involving US adults aged 50 and above found that older people with dementia experienced a decline in mobility (27). However, the current evidence on the trajectory of cognitive function in people with different disability levels remains limited. To date, no published studies in China have explored the trajectories of cognitive function and disability together.

Studies have shown that cognitive function trajectories are associated with genetics, the presence of other diseases, lifestyles, and socioeconomic status. Existing evidence suggests that the AOPEε4 gene may accelerate cognitive decline (39–41). Mental disorders, cardiovascular disease, and other chronic diseases have been identified as major contributors to accelerating declines in both cognition and mobility (42–44). In terms of lifestyle, poor nutrition and physical inactivity worsen both physical disability and cognitive function (45, 46). Previous studies have also revealed that education, income, occupation, and residential surroundings can differentially affect the rate of cognitive and disability decline in the older people (47–49). However, studies among China's older population have mainly focused on the effects of factors such as gender, disease, and education (50); there is a lack of comprehensive analysis of multiple factors.

This study was designed to reveal the trajectories of both cognitive function and physical disability among older people in China, and to identify the factors contributing to them, utilizing data from the China Health and Retirement Longitudinal Survey (CHARLS) (51), a prospective study with a national cohort, spanning from 2011 to 2018. The results have important implications for developing practical strategies to address current issues facing the aging Chinese population.

Methods

Participants and setting

CHARLS survey data from 2011, 2013, 2015, and 2018 were used. A total of 7,961 persons aged 60 and above were included in this study from the 2011 baseline of 17,708 respondents. We further excluded those who were lost to follow up (1,094 in 2013, 795 in 2015, and 892 in 2018) and 469 persons whose test results for cognitive function and physical disability were missing, resulting in a final study population sample size of 4,441 (see Figure 1).

Outcome measurements

Physical disability

Physical disability was assessed using scales of activities of daily living (ADL) and instrumental activities of daily living (IADL). Six questions (on bathing, dressing, eating, getting up/out of bed, toileting,

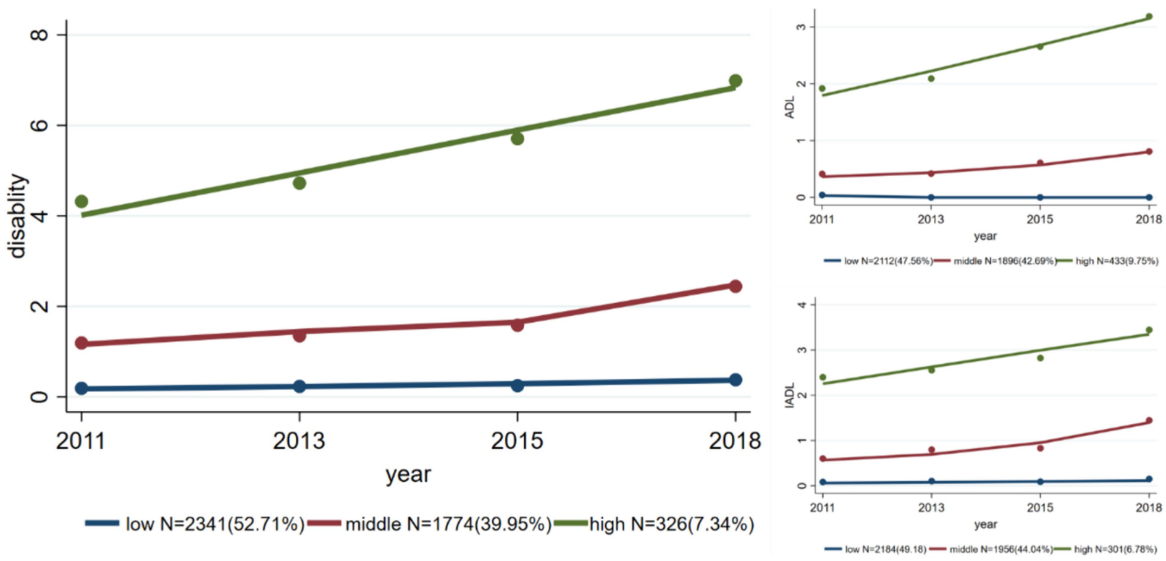

FIGURE 1
Trajectories of overall physical disability and of disability assessed by ADL and IADL separately.

and bowel control) were included in the ADL scale and five questions (on chores, cooking, shopping, phone calls, and medication) were included in the IADL scale. In the original questionnaire (52, 53), the responses to each question were divided into four levels ('no difficulty', 'difficult but still able to complete', 'difficult and need help', 'unable to complete'). In this study, any level of difficulty was defined as the presence of disability, and 'no difficulty' was defined as the absence of disability. This approach generated a disability score between 0 and 11, with a higher number indicating more limitation in daily activities.

Cognitive function

Two components of cognitive function were measured: episodic memory and psychiatric status (53–56). Reverse scoring was adopted, with a higher score representing poorer cognitive function. Episodic memory was measured by testing the respondents' ability to recall words, with 10 words tested for immediate memory and 10 for delayed memory. A wrong answer scored 1 point and a correct answer scored 0 points, yielding a total score ranging from 0 to 20 points, with higher scores representing worse episodic memory (57). Psychiatric status was measured by the time orientation, numeracy, and constructive drawing abilities of the survey respondents (58). The time orientation measurement asked the respondents the year, month, day, season, and day of the week at the time of the survey, with a wrong answer scoring 1 point and a correct answer scoring 0 points. Numeracy was measured by asking the respondents to calculate 100 minus 7 five consecutive times, with each wrong answer scoring 1 point and each correct answer 0 points. Constructive drawing ability was measured by asking the respondents to draw from a graphic shown by the investigator, with 0 points being assigned for correct drawings and 1 point for each error. The total cognitive function scores ranged from 0 to 31, with higher scores representing poorer cognitive function.

Covariates

The covariate data collected were age (60–69 years, 70–79 years, ≥80 years), gender (male, female), education (illiterate, elementary school, junior high school, high school and above), marital status (no partner, partnered), type of residence (rural, urban), region (eastern, central, western), annual household income (RMB0–9,999, RMB10,000–49,999, ≥RMB50,000), and type of medical insurance (Urban Employee Basic Medical Insurance, Urban and Rural Resident Basic Medical Insurance, Other).

Statistical analysis

The physical disability scores, including the total scores and scores for ADL and IADL, in the four survey waves were described by *n* (%). Medians (interquartile ranges) were used to describe the cognitive function scores, including total scores and the scores for episodic memory and psychiatric status.

Group-based trajectory modeling (GBTM) (59, 60) was employed to identify similarities in the developmental trajectories of cognitive function and physical disability among the participants. Referring to previous studies, most of which have identified three groups of trajectories (17–21), we *a priori* set three as the number of groups. The respondents were categorized into the groups to which the progression patterns of their three trajectories had the maximum predicted probability of belonging. Next, we used chi-square tests to test the differences in baseline characteristics among the three groups. GBTM was conducted separately for the total disability scores, scores for ADL and IADL, total cognitive function scores, scores for episodic memory, and scores for psychiatric status.

For trajectories considering both physical disability and cognitive function simultaneously, we first divided all the participants into two subgroups based on the disability scores: absence of disability ('non-disabled'; disability score = 0) and presence of disability ('disabled'; disability score ≥ 1). The cognitive function trajectory was then identified separately for the two subgroups using GBTM. In line with the aforementioned analysis, we *a priori* set three groups for

GBTM and employed chi-square tests to analyze the differences in baseline characteristics.

A multinomial logistic regression model was used to analyze the factors influencing the trajectories of disability and cognitive function separately. The covariates were age, gender, education, marital status, type of residence, region, annual household income, and type of medical insurance. Due to limited sample size, we did not use a multinomial logistic regression model to identify the factors influencing the trajectories of cognitive function for subgroups with the presence and absence of disability. In addition, two sensitivity analyses were conducted to examine (1) the potential interactions of baseline cognitive function/physical disability score with other characteristics on physical disability and cognitive function trajectory, respectively, and (2) the potential moderation of hypertension on physical disability and cognitive function trajectory. Because, hypertension is important as comorbidities need to be taken in account as it is very frequent and is a risk factor for cognitive impairment and physical disability.

The software packages R 4.2.3 and Stata 17.0 were used for the statistical analyses, and the two-tailed test level of α was 0.05.

All waves of CHARLS were approved by the Institutional Review Board (IRB) of Peking University (IRB00001052-11015 for household survey and IRB00001052-11014 for biomarker collection). All participants signed informed consent.

Results

Baseline characteristics of the surveyed population

As shown in Table 1, the majority of the participants were aged 60–69 years (71.8%) at baseline, and approximately half were women (51.3%). Many were illiterate (34.8%) or had only a primary school education level (46.8%). A small number of the participants had no partner (18.1%). Although a minority were from urban areas (17.6%), the regional distribution was relatively even (37.7% from eastern China, 36.2% from central China, and 26.1% from western China). The annual household income of more than half of the participants was less than RMB10,000 (58.9%), and the main type of medical insurance was medical insurance for urban and rural residents (80.5%).

Physical disability and cognitive function across four survey waves

Table 2 shows the disability and cognitive function scores across the four survey waves. The proportion of participants free of physical disability gradually decreased from the 2011 to 2018 survey waves, with percentages of 65.9, 57.4, 51.0, and 46.6%. Few participants had a disability score above 5 points (<5%). The same trend was observed for IADL measurements, with the proportion of participants without physical disability being 74.6, 64.3, 59.7, and 53.5% for each survey wave. Compared with that of IADL disabilities, the prevalence of ADL disabilities was slightly lower, with the corresponding percentages of disability-free participants being 78.6, 78.1, 71.6, and 68.7%, respectively.

The cognitive function of the participants also deteriorated over the four waves of the survey, with the median cognitive function score increasing from 18 points in the 2011 wave to 19 points in 2013 and 2015, and 22 points in the 2018 wave. As an element of cognitive function, the psychiatric status worsened, with the median score rising from 4 points in 2011 to 5 points in 2013 and 2015, and 6 points in the 2018 wave. Meanwhile, deterioration in episodic memory occurred more slowly, with the median score increasing from 14 points in 2011 to 15 points in the 2018 wave.

Trajectories of disability and cognitive function

Three disability trajectories are shown in Figure 1. The trajectory with the consistently lowest level of disability was denoted the LOW group. This group ($N=2,341$) maintained a low disability level across the four survey waves and accounted for 52.71% of the total participants. The participants ($N=1,774$, 39.95%) with a somewhat higher disability level at baseline were categorized as the MIDDLE group. The disability score in this group started at a relatively low level, increased slowly from the 2011 to the 2015 wave, but then increased more rapidly in later years. The group with the highest baseline disability level, the HIGH group, contained the smallest number of participants ($N=326$, 7.34%). The disability score of this group increased rapidly from 4 in 2011 to approximately 7 in the 2018 wave. The trajectories of disability assessed using ADL and IADL showed similar trends (Figure 1).

Figure 2 shows three cognitive function trajectories. The LOW group started with the best cognitive function and consistently maintained a score of approximately 14 points (out of 20) across the four survey waves. This group accounted for 34.81% of the total participants ($N=1,546$). The MIDDLE group comprised participants with marked declines in cognitive function. In this group ($N=1,631$, 36.73%), the cognitive function score was approximately 18 points in the 2011 wave, but dramatically increased to approximately 23 points in the 2018 wave. The HIGH group, i.e., the group with the worst cognitive function, had a baseline score of over 24 points, which rapidly increased to approximately 28 points by the 2018 wave, and represented 28.46% of the total respondents ($N=1,264$). The trajectories of episodic memory and psychiatric status showed similar trends.

Figure 3 shows the trajectories of cognitive function in the disabled and non-disabled subgroups. Although the trajectories of the three groups in each subgroup showed the same trend, the cognitive function scores in the disabled group were lower than those in the non-disabled group. In terms of the distribution of participants, the non-disabled subgroup had more participants in the LOW disability trajectory group ($N=1,147$, 39.19%) than the disabled group did ($N=427$, 28.20%), but had fewer participants in the MIDDLE (36.76% vs. 42.60%) and HIGH disability trajectory groups (24.05% vs. 29.19%).

Factors influencing the trajectories of physical disability and cognitive function

The association between various factors and the trajectories of physical disability and cognitive function are shown in Figure 4. Compared with the LOW disability trajectory group, the risk factors

TABLE 1 Baseline characteristics of the participants.

Baseline characteristics	Overall	Disability trajectory group			*P*	Cognitive function trajectory group			*P*
		Low	Middle	High		Low	Middle	High	
N	4,441	2,341	1,774	326		1,546	1,631	1,264	
Age (years), *N* (%)					<0.001				<0.001
60–69	3,190 (71.8)	1,876 (80.1)	1,139 (64.2)	175 (53.7)		1,288 (83.3)	1,209 (74.1)	693 (54.8)	
70–79	1,099 (24.7)	427 (18.2)	546 (30.8)	126 (38.7)		241 (15.6)	389 (23.9)	469 (37.1)	
80–	152 (3.4)	38 (1.6)	89 (5.0)	25 (7.7)		17 (1.1)	33 (2.0)	102 (8.1)	
Sex, *N* (%)					<0.001				<0.001
Male	2,164 (48.7)	1,375 (58.7)	672 (37.9)	117 (35.9)		967 (62.5)	833 (51.1)	364 (28.8)	
Female	2,277 (51.3)	966 (41.3)	1,102 (62.1)	209 (64.1)		579 (37.5)	798 (48.9)	900 (71.2)	
Education, *N* (%)					<0.001				<0.001
No formal education	1,547 (34.8)	536 (22.9)	838 (47.2)	173 (53.1)		82 (5.3)	515 (31.6)	950 (75.2)	
Primary school	2,080 (46.8)	1,204 (51.4)	752 (42.4)	124 (38.0)		838 (54.2)	949 (58.2)	293 (23.2)	
Junior middle school	542 (12.2)	397 (17.0)	123 (6.9)	22 (6.7)		394 (25.5)	130 (8.0)	18 (1.4)	
Middle school or above	272 (6.1)	204 (8.7)	61 (3.4)	7 (2.1)		232 (15.0)	37 (2.3)	3 (0.2)	
Marital status, *N* (%)					<0.001				<0.001
Partnered	3,638 (81.9)	2,020 (86.3)	1,369 (77.2)	249 (76.4)		1,372 (88.7)	1,356 (83.1)	910 (72.0)	
Single	803 (18.1)	321 (13.7)	405 (22.8)	77 (23.6)		174 (11.3)	275 (16.9)	354 (28.0)	
Residence status, *N* (%)					<0.001				<0.001
Rural	3,661 (82.4)	1,811 (77.4)	1,561 (88.0)	289 (88.7)		1,046 (67.7)	1,435 (88.0)	1,180 (93.4)	
Urban	780 (17.6)	530 (22.6)	213 (12.0)	37 (11.3)		500 (32.3)	196 (12.0)	84 (6.6)	
Geographic distribution, *N* (%)					<0.001				<0.001
Eastern China	1,675 (37.7)	1,002 (42.8)	593 (33.4)	80 (24.5)		645 (41.7)	601 (36.8)	429 (33.9)	
Central China	1,607 (36.2)	811 (34.6)	657 (37.0)	139 (42.6)		602 (38.9)	589 (36.1)	416 (32.9)	
Western China	1,159 (26.1)	528 (22.6)	524 (29.5)	107 (32.8)		299 (19.3)	441 (27.0)	419 (33.1)	
Household family income per year (RMB), *N* (%)					<0.001				<0.001
0–9,999	2,614 (58.9)	1,222 (52.2)	1,168 (65.8)	224 (68.7)		745 (48.2)	991 (60.8)	878 (69.5)	
10,000–49,999	1,467 (33.0)	881 (37.6)	498 (28.1)	88 (27.0)		642 (41.5)	526 (32.3)	299 (23.7)	
50,000+	360 (8.1)	238 (10.2)	108 (6.1)	14 (4.3)		159 (10.3)	114 (7.0)	87 (6.9)	
Medical insurance, *N* (%)					<0.001				<0.001
Urban and Rural Resident Basic Medical Insurance	3,577 (80.5)	1,779 (76.0)	1,516 (85.5)	282 (86.5)		1,044 (67.5)	1,401 (85.9)	1,132 (89.6)	
Urban Employee Basic Medical Insurance	436 (9.8)	322 (13.8)	99 (5.6)	15 (4.6)		327 (21.2)	91 (5.6)	18 (1.4)	
Other	428 (9.6)	240 (10.3)	159 (9.0)	29 (8.9)		175 (11.3)	139 (8.5)	114 (9.0)	

TABLE 2 Disability and cognitive function scores across the four survey waves (*N* = 4,441).

	2011	2013	2015	2018
Disability score[a], *N* (%)				
0	2,927 (65.9)	2,548 (57.4)	2,266 (51.0)	2,071 (46.6)
1	632 (14.2)	918 (20.7)	956 (21.5)	863 (19.4)
2	333 (7.5)	361 (8.1)	417 (9.4)	410 (9.2)
3	162 (3.6)	206 (4.6)	230 (5.2)	270 (6.1)
4	100 (2.3)	131 (2.9)	184 (4.1)	203 (4.6)
5	87 (2.0)	80 (1.8)	114 (2.6)	153 (3.4)
6	58 (1.3)	63 (1.4)	85 (1.9)	135 (3.0)
7	53 (1.2)	40 (0.9)	56 (1.3)	88 (2.0)
8	26 (0.6)	41 (0.9)	58 (1.3)	69 (1.6)
9	35 (0.8)	25 (0.6)	36 (0.8)	64 (1.4)
10	18 (0.4)	20 (0.5)	23 (0.5)	60 (1.4)
11	10 (0.2)	8 (0.2)	16 (0.4)	55 (1.2)
ADL score, *N* (%)				
0	3,491 (78.6)	3,468 (78.1)	3,179 (71.6)	3,053 (68.7)
1	501 (11.3)	505 (11.4)	613 (13.8)	591 (13.3)
2	203 (4.6)	228 (5.1)	299 (6.7)	301 (6.8)
3	104 (2.3)	103 (2.3)	157 (3.5)	181 (4.1)
4	68 (1.5)	70 (1.6)	99 (2.2)	125 (2.8)
5	53 (1.2)	51 (1.1)	62 (1.4)	103 (2.3)
6	21 (0.5)	16 (0.4)	32 (0.7)	87 (2.0)
IADL score, *N* (%)				
0	3,313 (74.6)	2,854 (64.3)	2,649 (59.7)	2,375 (53.5)
1	522 (11.8)	920 (20.7)	985 (22.2)	899 (20.2)
2	285 (6.4)	332 (7.5)	381 (8.58)	437 (9.8)
3	166 (3.7)	189 (4.3)	221 (4.98)	321 (7.2)
4	96 (2.2)	101 (2.3)	133 (2.9)	225 (5.1)
5	59 (1.3)	45 (1.0)	72 (1.6)	184 (4.1)
Cognitive function score (median [interquartile range])	18.00 [14.00, 23.00]	19.00 [14.00, 24.00]	19.00 [15.00, 24.00]	22.00 [15.00, 28.00]
Episodic memory score (median [interquartile range])	14.00 [11.00, 17.00]	14.00 [11.00, 17.00]	15.00 [12.00, 17.00]	15.00 [12.00, 20.00]
Psychiatric status score (median [interquartile range])	4.00 [1.00, 7.00]	5.00 [1.00, 8.00]	5.00 [2.00, 8.00]	6.00 [3.00, 9.00]

[a]Disability score is the sum of ADL and IADL scores.

for the MIDDLE group were an age of 70–79 years (odds ratio [OR]: 2.089; 95% confidence interval [CI]: 1.778, 2.456) or 80 years and older (3.879; 2.556, 5.887); being female (1.913; 1.654, 2.213); and living in the central (1.628; 1.392, 1.904) and western (1.697; 1.431, 2.012) regions of China. The protective factors were primary school (0.585; 0.501, 0.683), junior high school (0.370; 0.287, 0.477), or high school or above (0.446; 0.313, 0.635) education; urban residence (0.639; 0.510, 0.801); and an annual household income of RMB10,000–49,999 (0.765; 0.658, 0.890) or more than RMB50,000 (0.634; 0.487, 0.825). The risk and protective factors for the LOW and HIGH groups were similar, although the estimated ORs were slightly different.

The factors associated with cognitive function trajectories were similar to those associated with physical disability trajectories. Compared with the LOW cognitive function trajectory group, the risk factors for the MIDDLE group were an age of 70–79 years (OR: 2.154; 95% CI: 1.745, 2.659) or 80 years and older (3.330; 1.697, 6.535); and living in the central (1.267; 1.058, 1.518) or western (1.534; 1.250, 1.812) regions of China. The protective factors for the MIDDLE group were primary school (0.198; 0.152, 0.256), junior high school (0.070; 0.051, 0.097), or high school or above (0.041; 0.026, 0.064) education; urban residence (0.512; 0.400, 0.655); and holding medical insurance for urban workers (0.565; 0.413, 0.775). The risk and protective factors

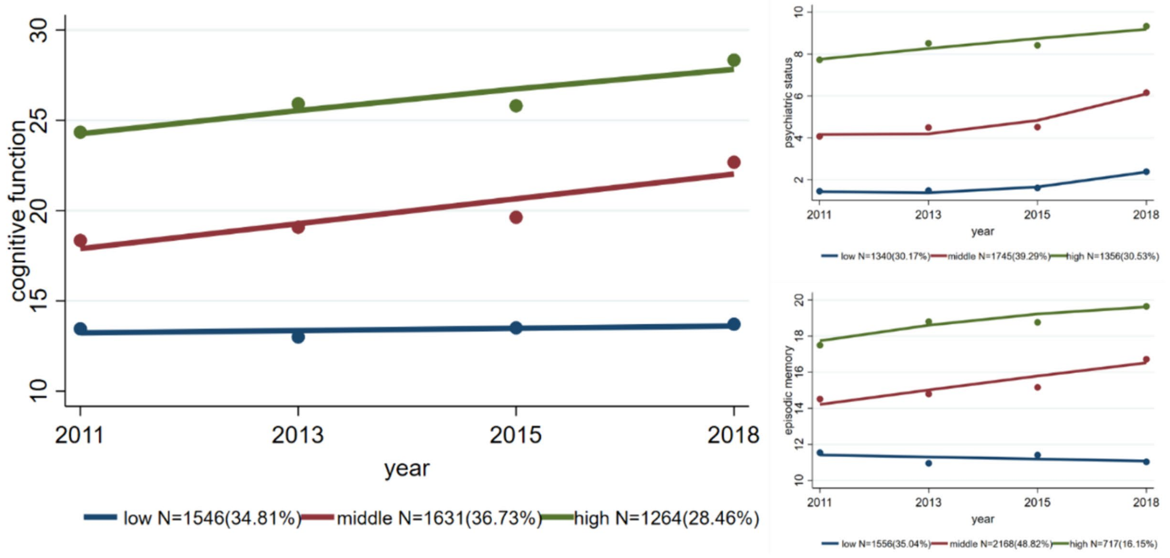

FIGURE 2
Trajectories of overall cognitive function, psychiatric status, and episodic memory.

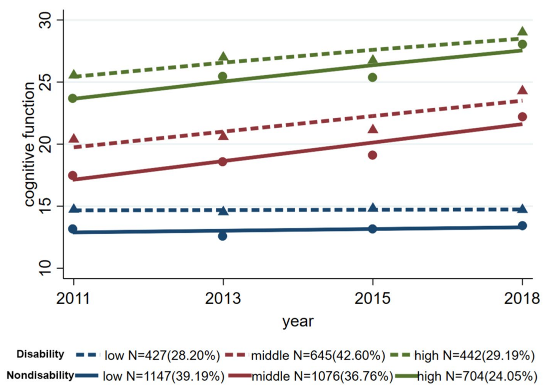

FIGURE 3
Trajectories of cognitive function in the disabled and non-disabled subgroups.

for the LOW and HIGH group were similar, although the estimated ORs were slightly different (Figure 4).

The differences in baseline characteristics between the trajectory groups, for both the disabled and non-disabled subgroups, are shown in Table 3. All baseline characteristics were significantly different among the three trajectories of cognitive function, regardless of disability status.

Sensitivity analyses showed that when examining the factors influencing physical disability trajectories (Supplementary Table S1), cognitive function score was a risk factor for both the MIDDLE group (OR: 1.24; 95:CI: 1.14, 1.34) and HIGH group (1.67; 1.50, 1.85), compared to LOW disability group. No significant interaction effect of cognitive function score with any characteristics was founded. Baseline physical disability score was not associated with cognitive trajectories (Supplementary Table S2), although the interaction of medical insurance and physical disability score was significant. Fourteen types of available comorbidities are summarized in Supplementary Table S3. Hypertension was associated with high cognitive trajectory group (1.58; 1.22, 2.05), compared to low group, and might also interact with education and residence status (Supplementary Table S4) to affect cognitive function trajectory. Regarding physical disability trajectory, hypertension was associated with both middle (1.84; 1.55, 2.19) and high disability trajectory groups (2.08; 1.46, 2.95), but no significant interaction of hypertension with other characteristics was observed (Supplementary Table S5).

Discussion

Based on a large prospective cohort in China, three trajectories for cognitive function and physical disability were identified in people aged 60 and above. Compared with those free of disability at baseline, a larger proportion of older people with disability at baseline showed rapid cognitive deterioration. Furthermore, we found that the trajectories of cognitive function and disability shared mostly the same contributing factors.

The development trajectories of cognitive function in the older Chinese people included in this study were categorized into LOW, MIDDLE, and HIGH groups, representing groups with stable good cognitive function, slightly worse cognitive function with dramatic progression, and the lowest level of cognitive function at baseline followed by rapid progression, respectively. These group features were consistent with the findings of Su et al. in China, in a study that was also based on CHARLS data and applied GBTM (2022) (21), Casanova et al. in the UK (2020) (61), and Hamilton et al. in the US (2021) (22), suggesting that older people from different countries may display similar patterns of progression in cognitive degeneration. However, we did not find a reversal trajectory as observed by Summers et al. in an Australian population, in which 24.7% of people aged over 60 with

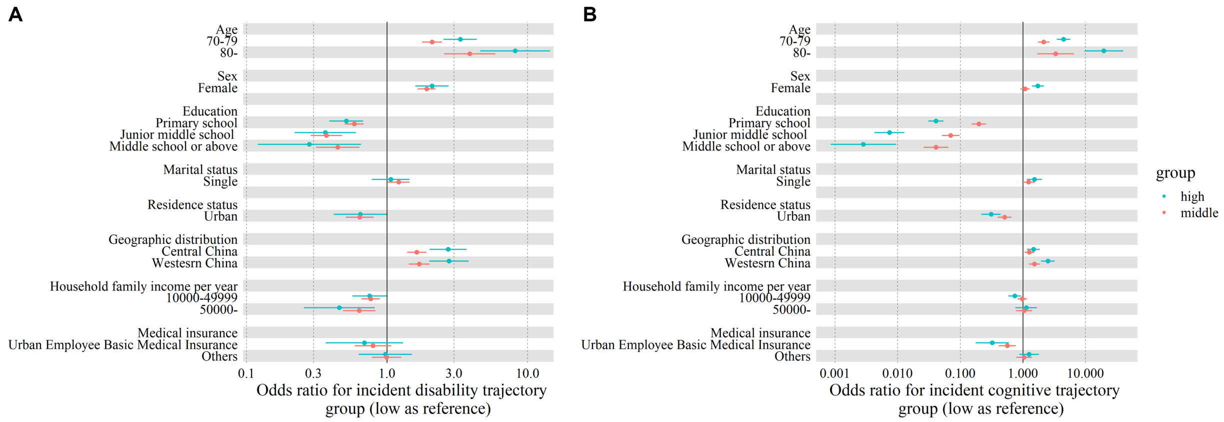

FIGURE 4
Odds ratios (ORs) and 95% confidence intervals (95% CIs) for factors associated with disability trajectory groups **(A)** and cognitive function trajectory groups **(B)**. Solid dots and error bars, respectively, denote the OR and 95% CI estimates.

mild cognitive impairment recovered to a level of unimpaired cognitive function over the following 20 months (62). Another study by Ye et al., based on the Chinese Longitudinal Healthy Longevity Survey cohort of Chinese people aged 65 and above and spanning 12 years, identified a group with a slight improvement in cognitive function over time. This group, accounting for 19.16% of the population, showed moderate levels of cognitive function at baseline and a slight increase in cognitive function by one point (20). The differences in the results of these studies may stem from variation in population characteristics, measurement tools, medical services, and other factors.

Because the causes of disability in older people are complex, the number and shape of disability trajectories have varied widely in previous studies (25, 26, 28, 63, 64). Nevertheless, regardless of the classification model, the disability trajectories of Chinese older people have consistently been categorized into three groups (24, 30, 31, 65–68). Most studies have shown that these groups exhibit the characteristics of a low disability level remaining consistent, a low baseline disability level followed by rapid development, and a high disability level with rapid development, respectively (24, 30, 65). These findings are in line with the trajectories identified in our study.

To the best of our knowledge, this is the first Chinese study to consider both disability and cognitive function together, which is of great significance in shedding light on co-morbidity in the older people. We found that the cognitive function levels in older people were characterized by the same three trajectories regardless of the presence or absence of physical disability at baseline. However, a greater proportion of the older individuals who had limitations in daily activities at baseline showed rapid declines in cognitive function post-baseline. These results to some extent validate the findings of Verlinden et al. (69), who established a link between cognitive function and disability; that is, dementia patients showed memory impairment, a decreased Mini Mental State Examination scale score, IADL restriction, and Basic Activities of Daily Living restriction in the 16 years before dementia diagnosis (69). In other words, physical disability in the older people accelerates the decline in cognitive function, which in turn worsens physical limitations.

In terms of the factors contributing to the identified trajectories of cognitive function, we found that more highly educated older people had higher baseline cognitive levels and were less likely to be on a rapid decline trajectory, which is consistent with previous findings (70–73). These results support the cognitive reserve hypothesis, which states that the brain is able to utilize available neural structures as a backup or reserve, and therefore education early in life can delay the clinical expression of dementia by influencing the brain's pathological response. This hypothesis has been validated in animal models (74). Casanova et al. indicated that the most prominent predictor of cognitive trajectory is education level (61). Even education in later life has been shown to protect cognitive function (75). As the prevalence and incidence of dementia among the older people in China with low education levels are on the rise (76), we suggest that educational efforts targeting middle-aged and older Chinese adults with low education levels may help reduce their risk of dementia and rapid cognitive deterioration.

Our findings suggest that, to some extent, a high socio-economic status helps maintain a high level of cognitive function and physical ability. In particular, household income was only associated with the trajectory characterized by a low physical disability level at baseline followed by rapid development. As household income decreased, the probability of an older person following this trajectory increased significantly ($OR_1 = 0.765$, $OR_2 = 0.634$). This phenomenon is consistent with the finding of Nusselder (77) that low-income groups were more likely to follow a trajectory characterized by a sudden increase in disability, because they were at an increased risk of disabling chronic diseases due to behaviors that were not beneficial to their health. In addition, Taylor et al. found that education, while effective in preventing the onset of disability, was less effective in slowing the progression of disability at a certain level of income (47). In other words, income may play a more crucial role in preventing disability than education. Therefore, in areas with better economic status, education for the older people may delay dementia, while in economically disadvantaged areas, vigorous economic development and creating economic security for the older people would be effective in reducing the overall degree of disability.

Notably, this study is the first to find that the type of medical insurance also affects the baseline cognitive levels and rate of cognitive

TABLE 3 Baseline characteristics of the groups in three cognitive function trajectories, by physical disability status.

Baseline characteristics	Cognitive function trajectory group in the disabled subgroup			*P*	Cognitive function trajectory group in the non-disabled subgroup			*P*
	Low	Middle	High		Low	Middle	High	
N	427	645	442		1,147	1,076	704	
Age (years), *N* (%)				<0.001				<0.001
60–69	352 (82.4)	449 (69.6)	200 (45.2)		963 (84.0)	805 (74.8)	421 (59.8)	
70–79	67 (15.7)	175 (27.1)	195 (44.1)		175 (15.3)	254 (23.6)	233 (33.1)	
80–	8 (1.9)	21 (3.3)	47 (10.6)		9 (0.8)	17 (1.6)	50 (7.1)	
Sex, *N* (%)				<0.001				<0.001
Male	238 (55.7)	254 (39.4)	112 (25.3)		743 (64.8)	592 (55.0)	225 (32.0)	
Female	189 (44.3)	391 (60.6)	330 (74.7)		404 (35.2)	484 (45.0)	479 (68.0)	
Education, *N* (%)				<0.001				<0.001
No formal education	37 (8.7)	283 (43.9)	362 (81.9)		53 (4.6)	303 (28.2)	509 (72.3)	
Primary school	249 (58.3)	326 (50.5)	77 (17.4)		607 (52.9)	641 (59.6)	180 (25.6)	
Junior middle school	99 (23.2)	29 (4.5)	3 (0.7)		298 (26.0)	100 (9.3)	13 (1.8)	
Middle school or above	42 (9.8)	7 (1.1)	0 (0.0)		189 (16.5)	32 (3.0)	2 (0.3)	
Marital status, *N* (%)				<0.001				<0.001
Partnered	378 (88.5)	523 (81.1)	300 (67.9)		1,021 (89.0)	896 (83.3)	520 (73.9)	
Single	49 (11.5)	122 (18.9)	142 (32.1)		126 (11.0)	180 (16.7)	184 (26.1)	
Residence status, *N* (%)				<0.001				<0.001
Rural	329 (77.0)	603 (93.5)	422 (95.5)		745 (65.0)	921 (85.6)	641 (91.1)	
Urban	98 (23.0)	42 (6.5)	20 (4.5)		402 (35.0)	155 (14.4)	63 (8.9)	
Geographic distribution, *N* (%)				<0.001				<0.001
Eastern China	163 (38.2)	189 (29.3)	134 (30.3)		485 (42.3)	434 (40.3)	270 (38.4)	
Central China	176 (41.2)	243 (37.7)	145 (32.8)		448 (39.1)	360 (33.5)	235 (33.4)	
Western China	88 (20.6)	213 (33.0)	163 (36.9)		214 (18.7)	282 (26.2)	199 (28.3)	
Household family income per year (RMB), *N* (%)				<0.001				<0.001
0–9,999	244 (57.1)	454 (70.4)	310 (70.1)		510 (44.5)	627 (58.3)	469 (66.6)	
10,000–49,999	152 (35.6)	159 (24.7)	109 (24.7)		508 (44.3)	362 (33.6)	177 (25.1)	
50,000–	31 (7.3)	32 (5.0)	23 (5.2)		129 (11.2)	87 (8.1)	58 (8.2)	
Medical insurance, *N* (%)				<0.001				<0.001
Urban and Rural Resident Basic Medical Insurance	334 (78.2)	583 (90.4)	403 (91.2)		740 (64.5)	904 (84.0)	613 (87.1)	
Urban Employee Basic Medical Insurance	59 (13.8)	16 (2.5)	3 (0.7)		267 (23.3)	74 (6.9)	17 (2.4)	
Others	34 (8.0)	46 (7.1)	36 (8.1)		140 (12.2)	98 (9.1)	74 (10.5)	

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decline in older people. In China, medical insurance is divided into two categories: medical insurance for urban workers and medical insurance for urban and rural residents. The former mainly covers employees, and the latter covers urban and rural unemployed people and freelance workers, such as housewives and farmers. Compared with urban and rural residents with medical insurance, urban workers with medical insurance tend to have higher salaries, to enjoy more social security after retirement, and to live in better neighborhoods. In this study, the vast majority of the participants held medical insurance for urban and rural residents. They faced a greater risk of being on the trajectory characterized by the lowest baseline cognitive level and rapid cognitive decline post-baseline. Therefore, we posit that the association between the type of medical insurance and the trajectory of cognitive function exists because this essential indicator encompasses economic income, living environment, and other factors. However, this finding requires further validation through future studies.

We found that women were at a greater disadvantage than men in terms of both baseline cognitive level and rate of cognitive decline. This aligns with the findings of other studies in Chinese older people (17, 72). This association is likely to operate through the mediating effects of nutrition, education, and social participation. Due to traditional norms prevailing in China in the mid-20th century, men enjoyed a higher status in the family, prioritized access to scarce resources like education and food, and higher levels of social participation and social support. Women, in contrast, were more likely to experience malnutrition (45, 78, 79), possess a lower level of education, and face a lack of social interaction (80–82), all of which have been identified in previous studies as risk factors for dementia. Similar patterns have been observed in older people in other developing countries, such as Brazil (83).

In the current study, being partnered played a positive role in maintaining cognitive function in older people. Research has indicated that the impact of marriage on cognition is primarily explained by marital quality and the duration of widowhood. Individuals in high-quality marriages tend to receive emotional support and care from their spouses, so higher marital quality is often associated with higher cognitive function (84). Another study (2019) indicated that the converse was also true, i.e., the cognitive level of widowed older people was lower than that of their non-widowed counterparts, and the likelihood of cognitive decline increased with the duration of widowhood. However, the effects of stressful life events, such as widowhood, on people's cognitive function were observed to be delayed, with a sharp decline in cognitive function emerging 4 to 6 years after late-life widowhood (85).

This study has some limitations. First, we identified the cognitive function trajectories of older people in disabled and non-disabled participants separately to explore the combined trajectory of physical disability and cognitive function, rather than identifying their covarying trajectory. This is due to the heterogeneity in the methods of assessing cognitive level and physical disability, with the former typically having a scoring system and the latter being assessed by the number of items of daily living in which impairments are experienced. Second, some potentially important variables were not included in the model due to their unavailability. For example, a large number of studies have confirmed that the APOE gene is a high-risk genetic factor for progression of dementia. Not adjusting for this factor may, to some extent, have biased the effect estimates of the factors that were tested.

Conclusion

In this study, the cognitive function trajectories of Chinese older people fell into three characteristic groups: those maintaining the highest level of cognitive function, those with a moderate baseline level of cognitive function and dramatic progression, and those with the lowest baseline level of cognitive function and rapid progression. The disability trajectories also fell into three characteristic groups: a consistently low disability level, a low initial disability level with rapid development, and a high baseline disability level with rapid development. Analyzing cognitive function and physical disability together, we found that compared with those without disability at baseline, a greater proportion of older people with disability at baseline experienced rapid cognitive deterioration. In addition, education, income, type of medical insurance, gender, and marital status were found to be instrumental in the progression of disability and cognitive function impairment in the older population. The results suggest that the Chinese government, focusing on the central and western regions and rural areas, should develop education for the older people and increase their level of economic security to slow the rate of cognitive function decline and disability among this age group in China. These could become important measures to cope with population aging.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://charls.charlsdata.com/pages/data/111/zh-cn.html.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or the patients'/participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

SC: Writing – review & editing, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft. RY: Data curation, Validation, Writing – review & editing, Formal analysis, Investigation, Writing – original draft. KW: Data curation, Investigation, Methodology, Software, Visualization, Writing – review & editing, Writing – original draft. QW: Formal analysis, Methodology, Supervision, Validation, Writing – review & editing, Investigation. HZ: Project administration, Resources, Supervision, Writing – review & editing, Conceptualization. LL: Project administration, Resources, Supervision, Writing – review & editing. WC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing. LS: Conceptualization, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Enhancement or suppression: a double-edged sword? Differential association of digital literacy with subjective health of older adult—evidence from China

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Background: The emergence of an aging society and the digital age makes healthy aging a hot topic in Chinese society. This paper explores the associations between digital literacy and the subjective health of older adult individuals in PR China, offering insights that May assist policymakers and service providers in developing strategies and interventions suited to the digital era, potentially enhancing the healthy aging process for this demographic in China.

Methods: This study utilized data from the China Longitudinal Aging Social Survey. Initially, demographic variables of 2086 individuals in the sample were analyzed. Subjective health differences among different populations and correlations between core variables were examined. Subsequently, multivariate linear regression and chain mediation methods were utilized to examine the relationships and potential pathways among the three dimensions of digital literacy and the subjective health of older adult individuals.

Results: (1) The subjective health status of older adult individuals in China was generally favorable, with an average score of 3.406 ± 0.764. (2) There was no direct correlation observed between the frequency of digital information use and the subjective health of the older adult ($b = -0.032$, $p > 0.1$). Digital entertainment information ($b = 0.294$, $p > 0.1$) did not show a significant effect, whereas life management information ($b = 0.437$, $p < 0.01$) demonstrated a positive association. Similarly, the use of smart healthcare devices ($b = 0.842$, $p < 0.001$) indicated a positive association (3) The frequency of digital information use indirectly enhanced the subjective health of the older adult through life management digital information and the use of smart healthcare devices, but had no indirect effect through entertainment and leisure digital information.

Conclusion: Digital literacy is significantly correlated with the subjective health of the older adult, especially when they acquire life management information and utilize smart healthcare devices. However, a potential negative relationship is suggested between digital entertainment information and the subjective health of older adult individuals. Therefore, digital infrastructure should have prioritized the provision of high-quality, age-friendly digital applications for the older adult. This approach could have better harnessed the potential of digitalization to enhance health and well-being in older adults.

KEYWORDS

information literacy, subjective health, older adult, healthy aging, digital health, wearable electronic devices, mediation analysis

1 Introduction

With the improvement of public health standards and nutritional conditions in China, the average life expectancy of Chinese people has increased to 78 years. Simultaneously, the number of births in China has sharply declined in recent years, making the rapid aging of the Chinese population an inevitable trend (1). According to data from the National Bureau of Statistics, in 2022, the population aged 65 and above reached 209 million, accounting for 14.9% of China's total population (2). This figure is expected to continue to grow. Aging is not only a trend in China, but also a global phenomenon. Data from the United Nations' "World Population Prospects 2022" showed that the number of people aged 65 and over is continually increasing worldwide. It is projected that this figure will rise from 761 million in 2021 to 1.6 billion by 2050. Therefore, the issue of how to achieve healthy aging for the older adult is increasingly receiving attention from countries around the world (3). Therefore, how to achieve healthy aging for the older adult in China is increasingly receiving attention. To address this long-term challenge, the Chinese government is actively exploring aging models that are suitable for China's national conditions, while also actively learning from the healthy aging models of other aging societies around the world. Among them, healthy aging empowered by digital information technology has received high attention. China has introduced the Internet for more than 30 years, and the popularity of various information technology applications based on the Internet is high. The older adult can also have wide access to these new digital information application technologies, including digital smart healthcare devices suitable for the older adult and other application technologies are gradually popularized in the market (4, 5). This makes it possible for digital information technology to empower healthy aging for the older adult.

1.1 Previous research and its limitations

Digital literacy(DL) is a multidimensional concept that not only encompasses technical skills for handling digital information but also deeper cognitive and social interaction abilities (6). Compared to digital competence, which focuses on information processing and content creation, and digital skills, which focus on the specific abilities required for digital tasks, digital thinking emphasizes innovation and critical thinking in the application of digital technologies. Digital literacy is a broader concept that includes digital cognition, digital thinking, and digital skills. Digital empowerment for the older adult in health and aging care has become a developmental trend in aging societies. Therefore, it is imperative to harness digital technologies judiciously to provide enhanced services and solutions for health and aging care (7). Meanwhile, previous research has revealed two contrasting associations between digital information technology and the health of the older adult: the "enhancement hypothesis" and the "suppression hypothesis." The enhancement hypothesis posits that digital information and communication technologies empower older adult individuals in managing their health (8, 9), thereby enhancing their self-management capabilities (10), and reshaping their approach to health management (11). Some studies have also found that internet use among the older adult contributes to a sense of belonging and self-esteem (12), alleviates depression (13), and that more frequent internet usage correlates with lower levels of social loneliness (14). DL among the older adult is consistently associated with better psychological health (15, 16), and is correlated with higher levels of life quality and well-being (17). On the other hand, the suppression hypothesis indicates that there May not be a direct association between DL and psychological health. The rapid pace of societal transformation may leave the older adult struggling to adapt, presenting a greater number of life challenges and a negative association with their psychological well-being (18). This is particularly challenging for those with lower socioeconomic status, including the older adult and low-income individuals. Insufficient acquisition of digital skills can exacerbate their health issues (19–22). Furthermore, the use of wearable health devices May induce technological anxiety among the older adult (23, 24), thereby affecting their psychological health.

Previous research has primarily investigated the correlation between internet usage frequency and the mental health of older adults (25), However, these studies have not sufficiently focused on the trend of digital health applications for this demographic, presenting certain limitations. Firstly, the frequency of internet use does not fully represent the DL of the older adult. DL includes not only digital usage skills but also digital cognition and socio-emotional dimensions (26). The European Commission's definition of digital competence for citizens encompasses five areas: information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving. In summary, DL is a multidimensional concept that includes skills for acquiring, selecting, sharing, and using digital information (27–29). Research on DL should shift from a single dimension of internet use frequency to a multidimensional analytical framework (30, 31). This study evaluates the DL of the older adult from three dimensions: digital information acquisition, digital information selection, and digital usage skills. Digital information acquisition is the foundation of DL, reflecting the basic survival and adaptive capabilities of the older adult in the digital society. Digital information selection, which entails the older adult's discernment of digital information that meets their needs following cognitive processes such as emotion and critique, reflects their information literacy and critical thinking skills. Digital usage skills, a core component of DL, refer to the proficiency of the older adult in utilizing digital devices and software. Secondly, while previous studies have predominantly addressed the dual "enhancing" and "inhibiting" aspects of internet use in relation to the health of older adults, they have primarily focused on variations in socio-economic status, with less emphasis on the correlation between digital content and the health of older adults (16, 32). The relationship between an individual's perceived health and the various kinds of digital information they encounter May vary among older adults, possibly because of differences in their abilities to understand and manage a range of digital content (19, 33). Thirdly, much of the past research has discussed the correlation between DL and the mental health of older adults, but there is a lack of research examining its relationship with the overall health of older adults, which encompasses both physical and mental health (34). Subjective health (SH), which integrates various personal and societal factors in the evaluation of health conditions, provides a more accurate reflection of an individual's overall health status (35, 36). SH is closely associated with mortality risk, and its predictive capacity for happiness and quality of life surpasses that of mental and physical health, and is also more precise than professional medical evaluations (37). Therefore, it is more appropriate to utilize the SH of older adults as a measure, rather than focusing exclusively on mental health.

1.2 Formulation of research questions

Upon reviewing previous research, this study identifies a critical issue that merits further refinement and exploration: examining the relationship between multidimensional DL and the SH of older adults from a multifaceted perspective. To address this issue, under the framework of multi-dimensional DL, the DL of the older adult is subdivided into three dimensions: digital information acquisition, digital information selection, and digital usage skills, among which digital information acquisition, is a prerequisite for the formation of DL in the older adult (38). These three dimensions are operationalized as three variables: the frequence of digital usage (FDU), digital information content, which includes life management information (LMI) and digital entertainment information (DEI), and the smart healthcare devices usage (SHDU). On this basis, it analyzes how the three dimensions of DL, which have a progressive relationship, jointly act on the SH of the older adult (Figure 1). The innovation of this study is the identification of digital information selection as a key dimension of DL. It explores how the demand for different types of digital information content is satisfied to enhance the SH experiences of older adults, revealing their diversity. In the context of the increasingly obvious trend of digitalization in Chinese society and societies around the world, and the increasingly prominent issue of healthy aging, this research helps to understand the relationship and mechanism between DL and healthy aging of the older adult from a multi-dimensional perspective more comprehensively, and provides a theoretical basis for optimizing DL and healthy aging services for the older adult at the policy level globally.

2 Literature review and research hypothesis

2.1 Frequency of digital usage and subjective health

The Internet, as a modern communication tool, exhibits a significant correlation with the psychological well-being and social engagement of older adult. The most basic function of the Internet is to facilitate interpersonal information contact and emotional exchange, helping people to gain social support. When the population mobility of a society increases, using the Internet can help the older adult contact their children who are not at home, which can reduce the loneliness of the older adult (39). Observations suggest that among older adults, long-term internet use is often concurrent with reports of physical and mental well-being, as well as with lower incidences of functional disabilities (40). For those older adult people with less social interaction, using the Internet and other digital technologies can help alleviate symptoms of depression (25, 41). In addition, access to the Internet can not only help the older adult maintain their social circle but also enhance the social network support of the older adult (17). This can broaden their social channels and facilitate their social interaction capabilities, potentially leading to an enhancement in the quality of their social interaction and social support (42). The older adult can expand their social capital through information and communication technology, which means that they can get more social support from digital media, and the pleasure and SH they get from life will be enhanced accordingly (43). Especially, there is a positive correlation between the degree of DL improvement and the sense of happiness among low-income groups (44). In summary, the increased FDU by the older adult May reduce depression and enhance happiness, and self-health assessment (45, 46). Based on this, the first hypothesis of this paper is derived.

> Hypothesis 1: There is a positive correlation between the frequency of digital usage and the subjective health of older adults.

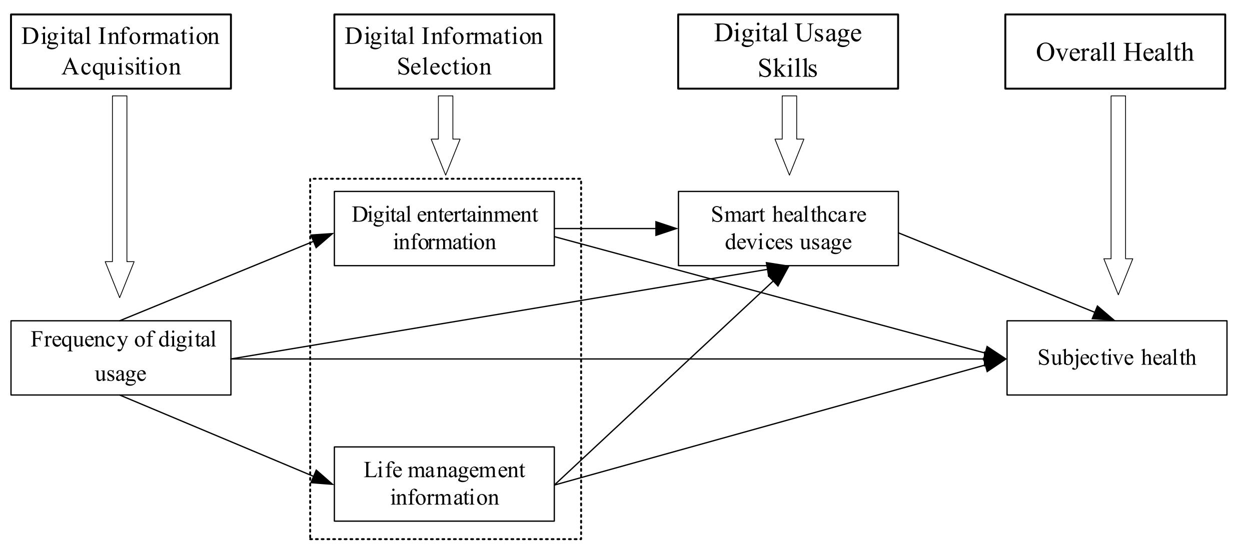

FIGURE 1
Analysis framework diagram.

> The higher the frequency of digital usage, the higher the level of their subjective health.

2.2 The mediating effect of digital information content

Most previous studies have suggested that older adult individuals' use of the internet for social interaction and information acquisition helps them gain support from family and society (17, 47), enhance their social cognition (48), and contributes to their subjective evaluation of their own health. However, the types of internet information accessed by the older adult are diverse. Although previous research has categorized the internet information accessed by the older adult into entertainment and leisure, life management, etc. (49, 50), there has been little in-depth comparison of the relationship between different types of internet information and the health of the older adult. The preference for digital information selection is a reflection of DL (51), as the older adult choose different types of digital information based on their varying needs and motivations (11), which May relate differently to their health.

There are two main viewpoints regarding the relationship between DEI and the health of the older adult: positive promotion and negative inhibition. The first viewpoint observes a correlation between light entertainment and leisure activities and the mental health of individuals (52), with online entertainment and leisure activities helping to restore attention (53), positively affecting self-cognitive abilities (54), and improving health indicators such as physical balance and processing speed (50, 55, 56). However, recent studies have found negative inhibition, suggesting that excessive use of entertainment digital technology, such as addiction to DEI, can pose health risks to the older adult. Long-term use of electronic devices is detrimental to their eyesight, causing discomfort or eye diseases (57). The degree of digital addiction negatively affects sleep quality, with the more digitally addicted older adult spending more time on social media, leading to poorer sleep quality (58). Reducing the use of DEI can lower levels of depression, anxiety, and stress (59).

Previous research has also examined the relationship between digital information and the daily life of the older adult. Studies have found that timely access to information on health management, shopping, transportation, and weather forecasts helps them manage their daily routines and expectations of life (32, 60). The comprehensiveness and diversity of digital information meet the diverse life management needs of the older adult. LMI is closely related to the daily lives of the older adult, helping to enhance their sense of control over life and boost their confidence and self-esteem, thereby promoting their SH. Such information is typically correlated with positive SH in the older adult (42). Digital participation is often associated with various aspects of social support, psychological well-being, and self-efficacy of the older adult, enhancing their quality of life and life satisfaction (61, 62). Health management is an important part of the older adult's life, and when they focus on health information, they actively acquire health information from online health information systems. Corresponding smart health systems support the older adult in acquiring, retrieving, and providing feedback on health information through human-computer interaction (63), making it easier for them to obtain health-related life information and promoting independent healthy living (64).

The relationship between digital information and the health of older adults is complex and multifaceted. On one hand, DEI May enhance the older adult's self-cognition, but excessive indulgence can harm their mental health. On the other hand, life management digital information is often positively associated with various health outcomes among the older adult. In summary, DEI and life management digital information have different relationships between FDU and SH. Thus, the second hypothesis of this paper is derived:

> Hypothesis 2a: Digital entertainment information has a negative mediating effect between the frequency of digital usage and subjective health.
>
> Hypothesis 2b: Life management information has a positive mediating effect between the frequency of digital usage and subjective health.

2.3 The mediating effect of smart healthcare device usage

The advent of digitization has led to the development and proliferation of smart healthcare devices, and the ownership and use of such devices by the older adult is an important dimension of DL. Previous research has found that the use of smart medical devices for electronic health monitoring can improve the health of the older adult (8). Smart wearable devices and immersive virtual reality devices suitable for the older adult can assist the older adult in obtaining health information, provide medical care monitoring, and help the older adult better manage their lives and health conditions (65, 66). These devices assist the older adult in their daily lives, meet the humanistic needs of the older adult with illnesses, improve their quality of life and daily functions (9, 67), enhance the confidence of the older adult in independent living (68), and improve the experience of the older adult in medical care (69). The process of the older adult SHDU can also enhance their understanding and participation in health issues (70), promote social interaction among the older adult about health care device information (71), and enhance their awareness of health communication. In addition, research has also found that smart healthcare devices have potential application value in coping with stress management (72), can have a positive impact on the physical and psychological health of the older adult, and improve their health management and quality of life (73). In general, through the use of digital information, it can promote the use of smart and digital health devices by the older adult, and have a positive significance for the health management and health perception of the older adult (74, 75). Based on this, the third hypothesis of this paper is derived.

> Hypothesis 3: The level of the smart healthcare devices usage has a positive mediating effect between the frequency of digital usage and subjective health.

2.4 The chained mediating effect of digital information content and SHDU

The choice of different digital information content by the older adult has different empowerment effects on their use of digital health care devices. Older adult people who pay more attention to LMI can access more digital life device information (76), can communicate with peers who have common needs about digital health care devices, and can acquire more digital health device usage skills (8). Moreover, it can also indirectly promote them to participate better in digital social activities (70), thereby improving the quality of their social interaction and social support (42), and then help the older adult to manage their health better (77). However, older adult individuals who focus on entertainment and leisure digital information, while still engaging in social interactions, tend to concentrate on entertainment topics rather than topics related to digital technology operation. These older adult individuals May face challenges such as insufficient skills and incomplete information when using digital healthcare devices. Although these challenges are not universal, they can exacerbate their anxiety towards digital technology and other psychological disorders (78, 79). Compared to older adult individuals who focus onLMI, those who concentrate on entertainment and leisure digital information might be less capable of using smart healthcare devices, leading to a lack of confidence in their own health due to insufficient skills in operating these devices. Combining the hypotheses on the relationship between digital information content and SH, as well as the relationship between the use of smart healthcare devices and SH among the older adult, we can propose the fourth hypothesis of this paper.

> Hypothesis 4a: Between the frequency of digital usage and subjective health, digital entertainment information and the smart healthcare devices usage have a negative chain mediating effect.
>
> Hypothesis 4b: Between the frequency of digital usage and subjective health, life management information and the smart healthcare devices usage have a positive chain mediating effect.

3 Methods

3.1 Data

This study utilized data from the China Longitudinal Aging Social Survey (CLASS), a nationwide survey conducted by Renmin University of China (RUC) on the mainland of China. The project systematically and regularly collected data on basic personal information, health and services, and socioeconomic status of Chinese older adults aged 60 and above (80). The survey sample covered 28 provinces in mainland China. The academic community highly recognized the quality, representativeness, and credibility of the survey data, and many scholars used this data to study the health status of Chinese older adults and its influencing factors. The survey of this research was reviewed and approved by the Scientific Research Ethics Committee at Renmin University of China, and all respondents signed a written informed consent (81). CLASS has not conducted any new surveys since 2019, and this paper used the survey data from 2018 as the analysis sample. The CLASS 2018 survey collected data from a total of 11,419 individuals aged 60 and above. This paper utilizes demographic variables from this survey, such as age and gender, as well as data on SH, FDU, digital information content, and the SHDU. Since the study of DL in the older adult is predicated on their engagement with the internet, this research focused solely on older adult individuals who have a history of internet use, resulting in a final dataset comprising 2,086 case studies.

3.2 Variables and measurement

3.2.1 Dependent variable

The dependent variable in this paper is SH. SH is an individual's overall assessment of their own health status. It integrates various personal and social factors in the evaluation of health status, reflecting the overall health status of an individual (35, 36). CLASS 2018 used two questions to measure this variable. (a) How do you feel about your current physical health status? The options used a five-point Likert scale, ranging from "very unhealthy" to "very healthy," coded as 1–5, respectively. (b) Compared with people of the same age, how do you feel about your health status? The options also used a five-point Likert scale, ranging from "much worse" to "much better," coded as 1–5, respectively. The Cronbach's alpha for the two items is 0.8166, indicating high reliability. Factor analysis was used to combine the two items into a SH factor. The higher the factor score, the healthier the respondents subjectively believed they were.

3.2.2 Independent variables

The independent variable in this study is DL, which specifically includes three dimensions: digital information acquisition, digital information selection, and digital usage skills. Digital information acquisition is fundamental to DL, mirroring the basic survival and adaptability of the older adult in a digital society. Therefore, this study operationalizes "digital information acquisition" as "the frequency of digital information usage." The frequency of usage reflects the extent of digital information intake and output among older adults. Consequently, the frequency of digital information usage is posited as a measure of the older adult's proficiency in obtaining digital information. CLASS2018 measured the internet usage of Chinese older adult individuals using three questions: "Do you use the internet?," "How frequently have you used the internet in the past 3 months?," and "How frequently have you used customized messages on your mobile phone in the past 3 months?." The options ranged from "never" to "always," coded from 1 to 5, respectively. The Cronbach's alpha for the three items is 0.7901, indicating relatively high reliability. Factor analysis was used to combine the three items into a digital information usage frequency factor. The higher the factor score, the higher the frequency of digital information use among the respondents.

The ability to select digital information refers to the capacity of the older adult to filter and adopt digital information that aligns with their personal needs and interests within a digital environment, through the application of critical thinking and emotional judgment. This process demands that older adults possess advanced cognitive assessment skills to discern and select content that is relevant and valuable from Internet platforms. The cultivation and enhancement of digital information selection skills are indispensable components in the construction of DL for the older adult, as they are directly linked to their advanced cognitive functions of information identification, evaluation, and decision-making. The questionnaire asked respondents, "What do you generally do online?" This multiple-choice question included options such as "text chatting," "reading news," "listening to music, watching videos," as well as "shopping," "transportation and travel," "health management," and "investment and financial management." If the respondent selected an option, it was coded as 1; otherwise, it was coded as 0. The first three items primarily involved entertainment and leisure content, while the latter four items involved life management content. Item response theory models were used to fit the first three items into a "digital entertainment information" index and the latter four items into a "life management information" index. Higher scores on these indices indicate a greater likelihood of the respondents using internet information for entertainment and leisure or life management, respectively.

Digital usage skills refer to the ability to use and operate digital technologies, platforms, and tools (82). The use of smart healthcare devices by the older adult to monitor their health status reflects their digital skills. Therefore, this study operationalizes "digital usage skills "as "the use of smart healthcare devices." The questionnaire asked respondents, "Have you used any of the following smart devices?" This multiple-choice question included options such as "smart wheelchair," "smart wristband," and "smart sleep monitor." If the respondent selected an option, it was coded as 1; otherwise, it was coded as 0. Item response theory models were used to fit the three items into a "use of smart healthcare devices" index. A higher index score indicates a higher level of use of smart healthcare devices by the respondents.

It should be noted that in the multivariate regression analysis stage, all three dimensions of DL were used as independent variables to analyze the relationship between the three dimensions and the SH of the older adult. In the mediation analysis stage, the FDU was used as the independent variable, and digital information content and the SHDU were used as mediating variables to analyze the correlation mechanism between the different dimensions of DL and SH among the older adult.

3.2.3 Control variables

The overall health status of older adults is associated with a multitude of factors, among which variables such as gender, age, and socio-economic status are common influencing factors (83, 84). Therefore, this paper uses variables that reflect demographic characteristics and socio-economic status, such as gender, age, years of education, marital status, place of residence, and individual annual income, as control variables. The gender variable was binary, with males coded as 1 and females coded as 0. Age was a continuous variable, with the ages of the older adult respondents in this study ranging from 60 to 108 years old. Years of education was a continuous variable, with no schooling, primary school, junior high school, high school, junior college, and undergraduate and above coded as 0, 6, 9, 12, 15, 16, respectively. Marital status was a binary variable, with married coded as 1, and unmarried or widowed coded as 0. Place of residence was an ordinal variable, with rural areas coded as 1, towns coded as 2, and cities coded as 3. Personal annual income was a continuous variable. For descriptive analysis, income was divided into four levels. In the multiple linear regression model, the logarithm of personal annual income was taken.

3.3 Statistical analysis methods

This study conducted data analysis using Stata 17.0. Firstly, descriptive analysis was performed on the demographic variables of the sample. Secondly, independent sample T-tests and variance analysis were used to compare the differences in SH among different demographic groups. Thirdly, a correlation analysis was conducted on the core variables of this study. Fourthly, a multiple linear regression analysis method was applied to analyze the effect of the main independent variables on the SH of the older adult. The mathematical expression is shown in Equation 1:

$$\begin{aligned} SH = b_0 + b_1 \times FDU + b_2 \times LMI + b_3 \times DEI + \\ b_4 \times SHDU + b_5 \times CV + e_1 \end{aligned} \quad (1)$$

Where SH is subjective health, b1, b2, b3, and b4 are the regression coefficients of the independent variables FDU, LMI, DEI, and SHDU, respectively, CV is the control variable, and e1 is the error term. Finally, a chained mediation statistical method was used to analyze the influence mechanism of the three dimensions of DL on the SH of the older adult. The mathematical expressions are shown in Equations 2–5:

$$LMI = b_6 \times FDU + b_7 \times CV + e_2 \quad (2)$$

$$DEI = b_8 \times FDU + b_9 \times CV + e_3 \quad (3)$$

$$SHDU = b_{10} \times FDU + b_{11} \times LMI + b_{12} \times DEI + b_{13} \times CV + e_4 \quad (4)$$

$$\begin{aligned} SH = b_{14} \times FDU + b_{15} \times LMI + b_{16} \times DEI + \\ b_{17} \times SHDU + b_{18} \times CV + e_5 \end{aligned} \quad (5)$$

Equations 2, 3 are the regression formulas for FDU on LMI and DEI for the older adult, respectively. Equation 4 is the regression formula for the use of FDU, LMI, and PDI on the SHDU by the older adult. Equation 5 is the regression formula for all independent and mediating variables on the SH of the older adult, where e2, e3, e4, and e5 are the error terms for each equation, respectively.

4 Result

4.1 Description of sample distribution

This study included a total of 2,086 valid cases. The demographic variables of the sample are presented in Table 1. In the sample, males (n = 1,092, 52.35%) were slightly more than females (n = 994, 47.65%). Most respondents were aged between 60 and 69 years (n = 1,631, 78.19%), followed by those aged 70–79 years (n = 386, 18.50%). Only a small portion of participants were aged 80–89 years (n = 61, 2.92%) or 90 years and above (n = 8, 0.38%). In terms of education level, secondary education (n = 879, 42.14%) was the most common, followed by those who had completed primary education (n = 519, 24.88%). A smaller portion of the older adult had completed high school education (n = 382, 18.31%) or held a bachelor's degree or higher (n = 127, 6.09%), and only a few had not received any school education (n = 179, 8.58%). Most older adult lived in urban areas (n = 1,417, 67.91%), with fewer living in rural areas (n = 431, 20.67%) or towns (n = 238, 11.41%), which is basically consistent with the current urban–rural distribution of the population in China. Most participants were married (n = 1,731, 82.98%), with a smaller proportion being unmarried or widowed (n = 355, 17.02%). In terms of religious beliefs, the vast majority of participants reported having no religious beliefs (n = 1,943, 92.71%), with a few reporting having religious beliefs (n = 152, 7.29%). In terms of monthly income, those with an income exceeding 7,500 yuan last year (n = 767, 36.77%) accounted for the largest proportion, followed by those with an income between 4,001 yuan and 7,500 yuan (n = 588, 28.19%), and

TABLE 1 Socio-demographic characteristics of the respondents.

Total		Frequency	Percentage
Gender	Female	994	47.65%
	Male	1,092	52.35%
Age (years)	60–69	1,631	78.19%
	70–79	386	18.50%
	80–89	61	2.92%
	≥90	8	0.38%
Educational level	No schooling	179	8.58%
	Primary school	519	24.88%
	Middle school	879	42.14%
	High school	382	18.31%
	Bachelor's degree and above	127	6.09%
Hometown	Rural	431	20.67%
	Towns	238	11.41%
	Cities	1,417	67.91%
Marriage	Unmarried or widowed	355	17.02%
	Married	1731	82.98%
Religious belief	No religious belief	1943	92.71%
	Religious belief	152	7.29%
Monthly income	< ¥1800	206	9.88%
	¥1800– ¥4,000	525	25.17%
	¥4,001– ¥7,500	588	28.19%
	> ¥7,500	767	36.77%

those with an income between 1,800 yuan and 4,000 yuan ($n = 525$, 25.17%). Those with an income below 1,800 yuan ($n = 206$, 9.88%) accounted for the smallest proportion.

4.2 Description of older adult subjective health status

Table 2 presented the overall SH level of the older adult, as well as comparisons of SH among different demographic groups. The SH variable in this paper ranged from 1 to 5 points, with statistics showing that the average score of SH for the older adult was 3.406 ± 0.764, indicating that the overall SH score of the older adult was relatively high. This paper also compared the SH of different groups based on demographic variables. When the group category was two, an independent sample T-test was used, and when the group category was three or more, a one-way analysis of variance was used. In terms of gender, the SH of males (3.440 ± 0.745) was significantly higher than that of females (3.368 ± 0.782), with a significant difference between the two ($t = -2.148$, $p < 0.05$). In terms of age, the SH level of the older adult aged 60–69 (3.447 ± 0.751) was significantly higher than those aged 70–79 (3.254 ± 0.791), 80–89 (3.311 ± 0.807), and 90 and above (3.188 ± 0.594), with a significant difference ($F = 7.240$, $p < 0.001$). In terms of education level, the SH of the older adult with a bachelor's degree or higher (3.592 ± 0.701) was significantly higher than that of the older adult with other education levels, with a statistically significant difference ($F = 11.670$, $p < 0.001$). In terms of residence, there was a significant difference in SH overall between rural (3.323 ± 0.826), town (3.433 ± 0.842), and city (3.427 ± 0.728) older adult people ($F = 3.210$, $p < 0.05$), with the SH level of town older adult people being higher than the other two groups. The SH score of married older adult people (3.424 ± 0.746) was significantly higher than that of unmarried or widowed older adult people (3.316 ± 0.839), with a significant difference ($t = -2.436$, $p < 0.05$). The SH of older adult people without religious beliefs (3.415 ± 0.756) was slightly higher than that of older adult people with religious beliefs (3.290 ± 0.844), but the difference was not significant ($t = 1.932$, $p > 0.05$). The SH status of older adult people with a monthly income exceeding ¥7,500 (3.486 ± 0.719) was significantly higher than that of older adult people with other income levels, with a statistically significant difference ($F = 9.420$, $p < 0.001$).

4.3 Correlation analysis

Table 3 presents the correlation coefficients, significance levels, and effect sizes among the key variables. As shown in Table 3, there are significant positive correlations between SH and the frequency of digital information use ($r = 0.116$, $p > 0.1$), entertainment and leisure ($r = 0.072$, $p < 0.01$), life management ($r = 0.120$, $p < 0.001$), and the use of smart healthcare devices ($r = 0.090$, $p < 0.001$). Additionally, the frequency of digital information use is significantly positively correlated with entertainment and leisure ($r = 0.125$, $p < 0.001$), life management ($r = 0.258$, $p < 0.01$), and the use of smart healthcare devices ($r = 0.164$, $p < 0.01$). There is a positive correlation between entertainment and leisure and life management ($r = 0.178$, $p < 0.001$), but a negative correlation between entertainment and leisure and the use of smart healthcare devices ($r = -0.048$, $p < 0.05$). Lastly, there is a positive correlation between life management and the use of smart healthcare devices ($r = 0.042$, $p < 0.1$). Although the correlations between these variables have all reached a significant level, when considering the R-squared values as indicators of the effect size for the correlation coefficients, all effect sizes are found to be small. To explore the relationship between DL and the SH of older adults, further multivariate linear regression and mediation analyses May provide additional insights.

4.4 Regression analysis

Table 4 displays the regression analysis results of DL on the SH of older adults. Model 1 is the baseline model, which includes only the control variables. The statistical results show that gender is significantly and positively associated with SH ($b = 0.077$, $p < 0.05$), indicating that male older adult individuals are psychologically healthier than females. Age is significantly and negatively associated with SH ($b = -0.019$, $p < 0.001$), indicating that among the older adult, the younger they are, the better their SH. Education level is significantly and positively associated with SH ($b = 0.026$, $p < 0.001$), suggesting that the higher the educational level of the older adult, the better their SH. Monthly income is significantly and positively associated with SH ($b = 0.080$, $p < 0.001$), indicating that the higher the income of the older adult, the better their SH. The association between the remaining control variables and the

TABLE 2 Comparison of subjective health among different population groups.

		Score	T(F)	p
Total		3.406 ± 0.764		
Gender	Female	3.368 ± 0.782	−2.148	0.032*
	Male	3.440 ± 0.745		
Age(years)	60–69	3.447 ± 0.751	7.240	0.000***
	70–79	3.254 ± 0.791		
	80–89	3.311 ± 0.807		
	>90	3.188 ± 0.594		
Edu	No schooling	3.215 ± 1.018	11.670	0.000***
	Primary school	3.333 ± 0.634		
	Middle school	3.274 ± 0.792		
	High school	3.407 ± 0.708		
	Bachelor's degree and above	3.592 ± 0.701		
Hometown	Rural	3.323 ± 0.826	3.210	0.041*
	Towns	3.433 ± 0.842		
	Cities	3.427 ± 0.728		
Marriage	Unmarried or widowed	3.316 ± 0.839	−2.436	0.015*
	Married	3.424 ± 0.746		
Religious belief	No religious belief	3.415 ± 0.756	1.932	0.053
	Religious belief	3.290 ± 0.844		
Monthly income	< ¥ 1800	3.179 ± 0.862	9.420	0.000***
	¥ 1800– ¥ 4,000	3.367 ± 0.863		
	¥ 4,001– ¥ 7,500	3.414 ± 0.669		
	> ¥ 7,500	3.486 ± 0.719		

*$p < 0.05$, ***$p < 0.001$.

TABLE 3 Correlation analysis.

	1	2	3	4	5
1. Subjective health (SH)	1.000				
2. Frequency of Digital Usage (FDU)	0.116*** (0.013)	1.000			
3. Digital entertainment information (DEI)	0.072** (0.005)	0.125*** (0.016)	1.000		
4. Life management information (LMI)	0.120*** (0.014)	0.258** (0.067)	0.178*** (0.032)	1.000	
5. Smart healthcare device usage (SHDU)	0.090*** (0.008)	0.064** (0.004)	−0.048* (0.002)	0.042⁺ (0.002)	1.000

Effect size in parentheses ⁺$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

SH of older adults is not statistically significant. Model 2 adds the FDU to Model 1. The coefficient for the FDU is significant ($b = 0.053$, $p < 0.05$), indicating that the higher the FDU among the older adult, the better their SH, thus confirming Hypothesis 1. Model 3 adds two variables related to the use of digital information content, namely DEI, and LMI, to Model 1. The statistical results show that the association between DEI and the SH of older adults is not significant ($b = 0.268$, $p > 0.1$), while LMI is significantly and positively associated with SH ($b = 0.5$, $p < 0.001$). This means that if older adult individuals use digital information mainly for life management, their SH will be better; conversely, if they use digital information mainly for entertainment and leisure, there is no significant alteration observed in their levels of SH. Model 4 adds the SHDU to Model 1. The statistical findings indicate a positive association between the use of smart health devices and SH ($b = 0.864$, $p < 0.001$), suggesting that the SHDU by the older adult contributes to their SH. Model 5 includes all control variables and the four variables encompassed by DL in the statistical analysis. The results show that LMI ($b = 0.437$, $p < 0.01$) and the SHDU ($b = 0.842$, $p < 0.001$) remain significantly positive, while the coefficients for the FDU and DEI are no longer significant.

4.5 Mediation analysis

Based on multiple linear regression analysis, this study used the SH of the older adult as the dependent variable, FDU as the independent variable, and digital information content and SHDU as mediating variables to form a chain mediation model. As shown in Figure 2, the path coefficients between the variables were presented, with the data outside the parentheses representing unstandardized path coefficients, and the data inside the parentheses representing standardized path coefficients. The FDU demonstrated positive associations with LMI ($b = 0.033$, $p < 0.001$), DEI ($b = 0.011$, $p < 0.001$), and SHDU ($b = 0.003$, $p < 0.05$), yet the direct effect of FDU on SH was not significant ($b = 0.032$, $p > 0.1$). DEI was negatively associated with SHDU ($b = -0.053$, $p < 0.05$), but its relationship with SH ($b = 0.294$, $p > 0.1$) was not significant, indicating no correlation between older adults' online entertainment activities and their proficiency in SHDU, nor a significant relationship with their SH. LMI showed positive associations with SHDU ($b = 0.025$, $p < 0.001$) and SH ($b = 0.437$, $p < 0.01$), suggesting that older adults' use of the Internet for life management could facilitate their technical skills in utilizing smart healthcare devices and was positively related to their SH. Lastly, SHDU was also positively associated with SH ($b = 0.842$, $p < 0.001$).

According to the mediation analysis results that were presented, the indirect effects of each mediating path were calculated as shown in Table 5. The path "FDU → DEI → SH" indicated no significant association between FDU and SH through DEI ($b = 0.0031$, $p > 0.1$), suggesting that older adults' use of the Internet for entertainment and leisure did not have a clear relationship with their SH, and Hypothesis 2a was not supported. The path "FDU → LMI → SH" showed a positive association between FDU and SH through LMI ($b = 0.0143$, $p < 0.01$), indicating that the use of the Internet for life management skills could contribute to the improvement of SH status in older adults, and Hypothesis 2b was supported. The path "FDU → SHDU → SH" indicated a positive association between FDU and SH through SHDU ($b = 0.0028$, $p < 0.05$), suggesting that SHDU significantly enhanced the SH level of older adults, and Hypothesis 3 was supported. The mediating path "FDU → DEI → SHDU→ SH" also

TABLE 4 Regression analysis of the impact of digital literacy on subjective health.

	Model 1	Model 2	Model 3	Model 4	Model 5
Gender (Male = 1)	0.077*	0.078*	0.065⁺	0.082*	0.071*
	(0.036)	(0.036)	(0.036)	(0.036)	(0.036)
Age	−0.019***	−0.018***	−0.017***	−0.019***	−0.017***
	(0.003)	(0.004)	(0.003)	(0.003)	(0.004)
Education	0.026***	0.024***	0.024***	0.025***	0.022***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
Marriage (Married = 1)	0.018	0.026	0.027	0.017	0.030
	(0.049)	(0.049)	(0.049)	(0.049)	(0.049)
Hometown (Urban = 1)	−0.019	−0.025	−0.021	−0.022	−0.027
	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)
Monthly income (ln)	0.080***	0.076***	0.073***	0.080***	0.070***
	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)
Frequency of Digital Usage (FDU)		0.053*			0.032
		(0.024)			(0.024)
Digital entertainment information (DEI)			0.268		0.294
			(0.216)		(0.216)
Life management information (LMI)			0.500***		0.437**
			(0.146)		(0.148)
Smart healthcare device usage (SHDU)				0.864***	0.842***
				(0.222)	(0.222)
Intercept	0.555*	0.421	0.319	0.578*	0.256
	(0.273)	(0.280)	(0.299)	(0.272)	(0.302)
N	2086	2086	2086	2086	2086
R^2	0.047	0.049	0.053	0.054	0.061
ΔR^2	—	0.002	0.006	0.007	0.014
p	0.000	0.000	0.000	0.000	0.000

Standard errors in parentheses $^{+}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

had a relatively small mediating coefficient ($b = -0.0005$, $p < 0.05$), indicating a certain negative association between FDU and SH of older adults through DEI and SHDU, and Hypothesis 4a was supported. The mediating path "FDU → LMI → SHDU→ SH "had a significant mediating coefficient ($b = 0.0007$, $p < 0.1$), indicating that FDU could positively associate with SH to some extent through LMI and SHDU, and Hypothesis 4b was supported.

5 Discussion

The digital construction and aging population are rapidly advancing worldwide. Effectively utilizing digital empowerment for healthy aging could contribute to addressing the global issue of population aging. Previous research primarily focused on the relationship between FDU and SH. This paper expands the research question to explore the relationship between DL and SH.

Research has found that the frequency of using digital information had no direct association with the SH of the older adult, which differs from previous studies (39, 40). FDU is significantly correlated with DEI, LMI, as well as with SHDU. Furthermore, there is a significant association between the use of LMI and SHDU with the SH perceptions of older adults. Thus, FDU May indirectly relate to SH through the intermediary roles of LMI and SHDU. Older adult individuals can use digital health devices like smart wristbands to provide personalized health monitoring tools, remote medical services, and health management applications, enabling them to better control their health status and enhance their self-efficacy in health management (68), thus allowing them to make more proactive health decisions. Moreover, LMI and SHDU have a positive chained mediating effect on the SH of the older adult, while DEI and SHDU have a negative chained mediating effect on their SH. This suggests that the content of digital information and the usage skills of smart healthcare devices have diverse relations with the SH of the older adult. DEI did not help the older adult master smart healthcare devices, thereby indirectly negatively relationship with their SH. In summary, the above findings indicate that most dimensions of DL are significantly associated with the SH levels of the older adult. However, the associations between the acquisition of digital information, the selection of digital information, and digital usage skills with the SH of the older adult are not entirely consistent. Further illustrating that DL is a comprehensive concept comprising multiple dimensions. Its internal structure is not only multi-dimensional, but there is also a certain progressive relationship among the different dimensions of DL.

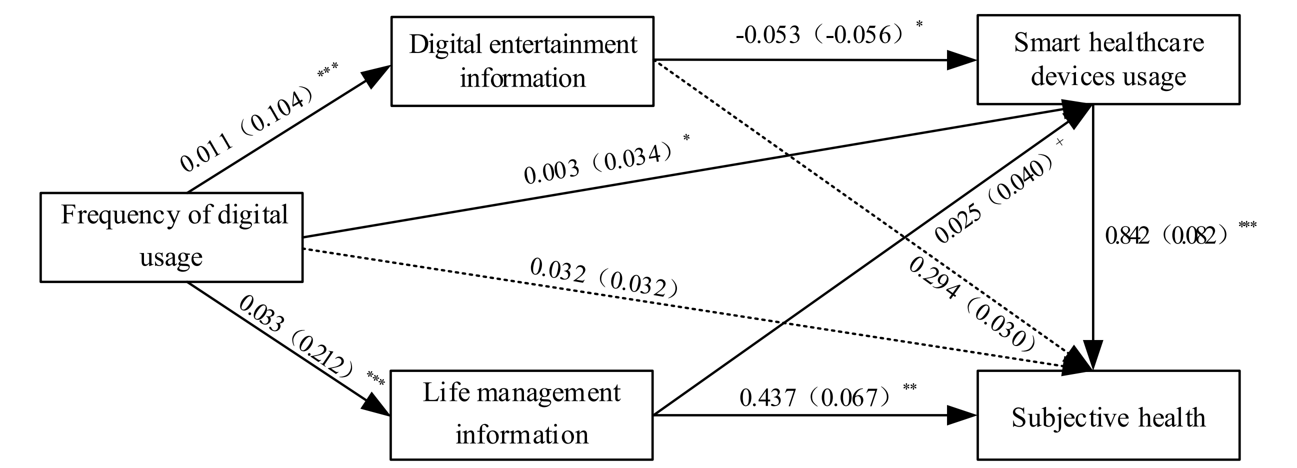

FIGURE 2
Path analysis diagram. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, The data outside the parentheses denote unstandardized coefficients, while the data within the parentheses denote standardized coefficients.

TABLE 5 Mediation effect decomposition.

	b	SE	*p*	95% CI
FDU → DEI → SH	0.0031	0.0024	0.205	(−0.0016, 0.0078)
FDU → LMI → SH	0.0143	0.0046	0.002	(0.0055, 0.0230)
FDU → SHDU → SH	0.0028	0.0014	0.045	(0.0001, 0.0057)
FDU → DEI → SHDU → SH	−0.0005	0.0002	0.049	(−0.0009, −0.0001)
FDU → LMI → SHDU → SH	0.0007	0.0004	0.066	(−0.0001, 0.0014)

FDU, frequency of digital usage; DEI, digital entertainment information (DEI); LMI, life management information; SHDU, smart healthcare devices usage; SH, subjective health.

Previous studies rarely consider the content of digital information for the older adult as a major dimension of DL, and even fewer classify digital information content. This paper attempts to supplement these deficiencies in previous research. The distinctive findings of this study elucidate the variegated associations between diverse digital information content and the perceived health status of older adults. Specifically, digital information pertaining to life management is positively linked with the SH of the older adult, whereas the correlation between entertainment and leisure digital content and the SH of this demographic is not markedly evident. This study suggests that the observed phenomenon is associated with the fulfillment of the older adult's life needs and that their self-assessment of health is linked to the extent to which their psychological needs are satisfied (85). LMI May help meet the life management needs of the older adult, help them better manage daily life, maintain healthy habits, plan retirement life, etc. (32, 60), enhance their autonomy, sense of competence, and seek support in life, thereby improving their quality of life, increasing life satisfaction, and enhancing their SH perception (61, 62).

Digital information for entertainment, such as online chatting, video streaming, and video games, exhibits multifaceted roles in meeting the needs of the older adult. On one hand, this type of digital information helps seniors pass the time in a relaxed atmosphere and, to some extent, aids in acquiring health knowledge through interactive entertainment, thereby enhancing their health awareness. It also contributes to improving their physical coordination and reaction speed. However, on the other hand, DEI can easily lead to addiction among the older adult, the experiences of diminished visual acuity, compromised sleep quality, and symptoms of anxiety May be correlated with internet addiction. Overall, Although digital information for entertainment and leisure has satisfied the recreational needs of the older adult to a certain extent, it also carries the potential to exert a negative influence on their SH. After the positive and negative aspects of this relationship neutralize each other, the association between digital information for entertainment and leisure and the SH of the older adult becomes non-significant. The "Uses and Gratifications" theory can elucidate the differentiated association between digital information content and the SH of the older adult. The older adult's preferences for digital information content are driven by their specific needs, which are met to varying degrees by different types of digital content. Consequently, they tend to prioritize content that most effectively addresses their most significant needs. In contrast to entertainment and leisure digital information, health-related and other life management digital information is more intimately connected with the daily lives of the older adult. This category of information is better positioned to meet the older adult's daily needs for health and wellness, suggesting a more substantial and evident connection between LMI and the SH perceptions of the older adult.

This study extends the investigation into the mechanisms linking DL with the SH of the older adult, analyzing the mechanisms underlying the differentiated relationships between various dimensions of DL and the SH of the older adult. Compared to previous research, The main innovation of this paper lies in the application of an expanded multidimensional DL framework to the older adult population, and the use of the "Uses and Gratifications" theory to elucidate the differences in the relationship between the digital information content selected under various needs and the SH of the older adult, thus expanding the explanatory scope of the "Uses and Gratifications" theory. This study enhances the understanding of healthy aging from a multidimensional DL perspective, providing significant policy implications for the ongoing digital construction and healthy aging initiatives across the globe. It is essential for digital infrastructure to deliver digital information that is accessible and suitable for the older adult, with a particular focus on supplying high-quality life management digital content. Additionally, establishing avenues to assist the older adult in mastering the use of digital health devices is crucial. These efforts collectively aim to elevate the older adult's comprehensive DL, thereby empowering them to better leverage DL for healthy aging.

This study acknowledges several limitations. The use of secondary data has constrained the operationalization of variables, particularly in the comprehensive assessment of DL and SH among the older adult. The measurement of variables was limited by the number of items and the binary approach used to assess the engagement with digital information content and the utilization of smart healthcare devices. This has led to relatively small effect sizes among the primary variables in this study, a lower *R*-squared value for the regression model, and minimal variation in the *R*-squared values across different models. Additionally, the absence of longitudinal data limits the inference of causality, which should be addressed in future research. Future research should adopt a more comprehensive and multidimensional approach to assessing SH and DL. This should involve enhancing the granularity and precision of variable measurement and data collection to more effectively investigate the explanatory power of DL on SH. Future inquiries should also analyze the interplay between DL and social factors, such as social capital, to comprehensively elucidate the mechanisms by which digital social dynamics influence the SH of the older adult following their integration into DL frameworks.

6 Conclusion

The findings of this study demonstrate a significant positive association between overall DL and SH among the older adult. The frequency of digital information use, LMI, and the SHDU are directly or indirectly linked to the SH of the older adult. Moreover, LMI and smart health devices exhibit a positive mediating effect between the frequency of digital information use and SH. In contrast, the chained relationship between entertainment and leisure digital information and smart health devices has a negative mediating effect between the frequency of digital information use and SH, while the direct effect of DEI on SH is not significant. These insights underscore the positive impact of enhancing DL among the older adult on their SH. Consequently, it is essential to provide the older adult with more life management digital information and to assist them in mastering the use of digital health devices, thereby better harnessing the empowering potential of digital construction for the health of the older adult.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Restrictions apply to the availability of these data. Data were obtained from the National Survey Research Center at the Renmin University of China and are available at http://class.ruc.edu.cn/, with the permission of the National Survey Research Center at Renmin University of China.

Ethics statement

Ethical approval was not required for the studies involving humans because the study utilizes data from the CLASS survey conducted by the Social Survey Center of Renmin University of China. The collection of data for this survey underwent a review of research ethics. The analysis performed in this study with this secondary data does not require an additional review of research ethics. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

Q-SY: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. QG: Data curation, Formal analysis, Software, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1395162/full#supplementary-material

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Impact of living arrangements and internet use on the mental health of Chinese older adults

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Introduction: The consequences of aged living arrangements on mental health in the digital age have drawn significant research attention.

Methods: This study used empirical data to analyze the impact of living arrangements on the mental health of older adults by ordinary least squares (OLS) and to examine the moderating effect of Internet use in it through the moderating effect test. A total of 17,243 older adults were included in the analytical model.

Results: We found that living independently has a negative impact on the mental health of older adults and Internet use can improve the mental health of older adults. There are moderating mechanisms of Internet use in the impact of living arrangements on the mental health of older adults, but it is necessary to look at the moderating mechanisms of different patterns of Internet use. Using the Internet for social interaction (chatting and information acquisition) can weaken the impact of living arrangements on the mental health of older adults, while unidirectional Internet use (entertainment and financial management) strengthens the impact of living arrangements on the mental health of older adults.

Disscusion: Therefore, this study puts forward the following suggestions: first, to develop family care for older adults and pay attention to the positive role of intergenerational support in the mental comfort of older adults; second, it is imperative for the government and social service departments to assist older adults in establishing correct concepts of Internet use, enhancing their digital literacy, and improving their digital skills.

KEYWORDS

living arrangements, internet use, mental health, older adults, China

1 Introduction

The global population aging trend is accelerating, and China's population is also aging at unprecedented levels. By the end of 2021, the number of people over 60 years old in China is as high as 260 million, accounting for 18.9% of the population of the country. Due to the increasing number of older adults, many issues related to it have gradually emerged and attracted the attention of the whole society. Among them, mental health is one of the hot topics (1). As a positive phenomenon (2), mental health is directly related to the quality of life for older adults. Therefore, it is crucial to fully recognize the importance of mental health for older adults (3).

As an important factor affecting the mental health of older adults, living arrangements have attracted much attention from scholars. Most research indicates that there is a close relationship between living arrangements and mental health among older adults (4–6); living arrangements have a significant effect on the risk of depression in older adults (7–9). There are two main views on the impact of living arrangements on the mental health of older adults. One view is that living with children is more beneficial to the mental health of older adults than living alone or only with a spouse. Studies have found that living with children is positively associated with the mental health of older adults (10). A contrary view is that living alone or only with a spouse is more favorable to the mental health of older adults. This is because living with children may lead to an over-reliance on their children's support, which may increase their sense of worthlessness and lead to cognitive impairment (11). Meanwhile, living with children may also lead to a high level of intergenerational conflict (12), which is not conducive to the mental health of older adults. At the same time, scholars have begun to pay attention to the ways in which living arrangements affect the mental health of older adults. Xu (13) found that the influence of living arrangements on the mental health of older adults depends on the sex of children who live with older adults and the living distance between children and their parents. Hamid et al. (14) further found that the interaction between living arrangements and social networks has a significant impact on the mental health of older adults. Regardless of living arrangements, older adults with strong social networks have better mental health than those who live alone and have fewer social networks. Although the relationship between living arrangements and the mental health of older adults has been discussed, the difference in the impact of different living arrangements on the mental health of older adults still needs further verification.

With the continuous increase in Internet use and the increasing popularity of mobile smartphones, more and more older adults use the Internet for shopping, traveling, social communication, and so on. Internet use is also silently having an impact on the mental health of older adults and has been widely discussed by scholars (15–17). On the one hand, research has found that Internet use has a positive impact on the mental health of older adults (18). While increasing older adults' self-efficacy (19), Internet use can also improve their loneliness (20–22), reduce their depression (23, 24), and decrease their mental distress (25). On the other hand, research has also found that Internet use can negatively affect the mental health of older adults. Using 2014 and 2016 CLASS data, Xie et al. (26) found that Internet use has a negative impact on the mental health of older adults and increases the incidence of depression in older adults.

The above studies mostly investigated the impact of living arrangements or Internet use alone on the mental health of older adults and rarely discussed the influence of both factors on mental health. Ecological system theory (27) holds that many factors related to individuals and the interaction between them will affect people's mental health. Therefore, based on the current Internet era, while considering the impact of living arrangements on the mental health of older adults, it is also necessary to include Internet use as a factor in order to better improve the mental health of older adults.

In summary, this study proposes the following hypotheses:

> *Hypothesis 1*: Older adults living independently have significantly poorer mental health than those who live with their children.
>
> *Hypothesis 2*: Older adults using the Internet have significantly better mental health than those who not using the Internet.
>
> *Hypothesis 2.1*: Older adults with available Internet connections have better mental health than those without available Internet connections.
>
> *Hypothesis 2.2*: The more frequently older adults use the Internet, the better their mental health.
>
> *Hypothesis 2.3*: Older adults who use the Internet for chatting, information acquisition, entertainment, or financial management have better mental health.
>
> *Hypothesis 3*: Internet use can modify the impact of living arrangements on the mental health of older adults by attenuating the negative effects of living independently.

2 Materials and methods

2.1 Data

The data in this paper come from the 2018 China Health and Retirement Longitudinal Study (CHARLS), which covers families and individuals aged 45 years and above for 150 county-level units and 450 village-level units across the country; 19,816 valid cases are fairly representative, especially for those in the older adult group. It covers basic personal information, physical health and function, psychological status, participation in basic endowment insurance and basic medical insurance, working situation, income status, and basic family information. This source provides detailed data to support the study of issues such as retirement. At the same time, these data also cover related to Internet use. Therefore, it can be applied to the study of the relationship between living arrangements, Internet use, and mental health for older adults. This paper defined older adults as those over 60 years old. Based on age, the sample selected in this paper was the population over 60 years old. After eliminating the missing and invalid variables, 17,243 valid cases were obtained.

2.2 Measurement

2.2.1 Dependent variable

The dependent variable in this study was the mental health of older adults. We used the Depression Index to measure mental health, measured by the CESD-10 (Center for Epidemiological Studies Depression Scale) in the CHARLS data (28). This scale contained 10 questions measuring respondents' mental health and depression levels, with a minimum score of 0 and a maximum score of 30. In the analysis presented here, scores above 10 were considered to be prone to depression, with higher scores indicating greater depression proneness and poorer mental health.

In this study, subjective life satisfaction was utilized as an alternative dependent variable to evaluate the robustness of the research outcomes. Consistent with prior scholarly endeavors, a statistically significant correlation has been established between the depression index (13) and subjective life satisfaction (29), which has been previously employed as a proxy variable for robustness assessment in certain research contexts. Our initial analysis further substantiates a robust correlation between these two constructs (correlation coefficient: −0.4536, achieving statistical significance at the 0.001 level). Therefore, we adopted subjective life satisfaction as an alternative dependent variable in our analysis. We utilized the item from the questionnaire: "Please think about your life-as-a-whole. How satisfied are you with it?" for measurement purposes. This is a five-category ordinal measurement. In this paper, responses in categories 1–3 were consolidated and treated as "satisfied," while those in categories 4 and 5 were merged as "dissatisfied," assigned with values of 1 and 0, respectively, resulting in a dichotomous dummy variable.

2.2.2 Independent variable

The independent variable was the living arrangements of older adults. Through the preliminary analysis, it was found that except for living alone, living with a spouse, and living with children, other types of cohabiting family structures only account for a small number. In addition, this paper focused on the intergenerational relationships associated with living arrangements. Therefore, this paper divided living arrangements into two categories: living independently (including living alone or living with a spouse only) (30) and living with children, and treated the other few categories as missing.

2.2.3 Moderating variable

The moderating variable was Internet use, which was users' behavior in terms of accessing Internet services through various terminal devices (including computers, tablets, and mobile phones). In a questionnaire survey, responses were elicited by asking the question, "Have you used the Internet in the last month." At the same time, Internet use was divided into three dimensions: available Internet connections, frequency of Internet use, and patterns of Internet use. Available Internet connections were measured according to whether the relevant terminal equipment is owned and whether the current housing has broadband access. The frequency of Internet use was examined by asking the question "What was the frequency of Internet access in the past month," which was treated as an interval-scale variable. Patterns of Internet use included chatting, information acquisition, entertainment, and financial management. The measurement is based on the question in the questionnaire, "What do you usually do on the Internet?" Answer 1 represents "chatting," and Answer 2 is "reading news," which we use to measure the functional use of information acquisition. Answer 5 is "financial management," which is used to measure the use of online financial functions. The remaining answers, "3. Watch videos" and "4. Play games," were consolidated and named "entertainment," while Answer "6. Others" was treated as missing. Based on this, a four-category variable was obtained and further processed into four binary dummy variables, each with values of 1 ("yes") and 0 ("no").

2.2.4 Control variables

Personal characteristics (sex, age, marital status, and physical health) and social structural characteristics (education level, total income, and place of residence) were included as control variables (Table 1).

2.3 Analysis strategy

2.3.1 OLS model

In this paper, the method of ordinary least squares (OLS) regression was used to estimate the impact of living arrangements on the mental health of older adults:

$$\text{Depression}_i = \alpha + \beta \bullet \text{Living}_i + \gamma \bullet X_i + \varepsilon_i \quad (1)$$

In Equation 1: $Depression_i$ is the value of the depression index of the i th older adult; $Living_i$ is the living arrangement of the i th older adult; Xi represents the personal and social structural characteristics of the i th older adult.

2.3.2 Robust test: PSM and alternative dependent variable

As the coefficient estimated by OLS regression may be affected by selectivity bias and reverse causality, this paper adopted the PSM (propensity score matching) method as a robustness test for OLS estimation. First, we utilized the logit model to predict the probability of individuals not living with their children, referred to as the propensity score. In this process, the controlled covariates X_i were the same as the control variables in the OLS model. Second, we matched individuals whose propensity scores were within a common range of values. In order to ensure the robustness of the results, we used four matching methods: nearest neighbor matching ($k = 1$), nearest neighbor matching within a radius, kernel matching, and local linear regression matching. Then, the sample balance test was carried out. Finally, we calculated the "average treatment effect on the treated" (ATT) from the matched samples.

To further test the reliability of the findings, this paper utilized life satisfaction from CHARLS (2018) as the explained variable to measure the mental health of older adults and repeated the empirical analysis process of the main model.

2.3.3 Heterogeneity analysis and chow test

In order to more carefully examine the differences in the study results between the different groups, the heterogeneity test was conducted by group regression. At the same time, the Chow test was used to test the significance of the difference between groups.

2.3.4 Moderating effect

In order to examine the moderating effect of Internet use, this paper used the moderating effect test, and this model was set up as follows:

$$Depression_i = \alpha_2 + \beta_2 \bullet Living_i + \gamma_2 \bullet X_i + \delta \bullet Internet_i + \phi \bullet Living_i \times Internet_i + \varepsilon_2 \quad (2)$$

$$Depression_i = \alpha_3 + \beta_3 \bullet Living_i + \gamma_2 \bullet X_i + \sum_{k=1}^{6} \delta_k \bullet Internet'_{ki} + \sum_{k=1}^{6} \phi_k \bullet Living_i \times Internet'_{ki} + \varepsilon_3 \quad (3)$$

In Equation 2: $Internet_i$ is the moderating variable, which is Internet use of older adults; and the rest of the variables and symbols have the same meaning as in Equation 1.

In Equation 3: To further investigate how Internet use plays a moderating role, this paper used behavioral characteristics of Internet use (availability of devices, frequency of Internet use, and patterns of Internet use) to analyze the mechanism of Internet use in the impact of living arrangements on the mental health of older adults.

3 Results

3.1 Empirical results and analysis

For the analysis of the effect of living arrangements on mental health, this study used OLS Regression. Model 1 includes independent variables only to build the benchmark model. Model 2 adds all the control variables to Model 1, and Model 3 adds Internet use to Model

TABLE 1 Definition of key variables and descriptive analysis (N = 17,243).

Variable		Definition	Mean	Std. dev.
Dependent Variable	Mental health	Measuring the level of depression index based on the depression scale CES-D(10):[0,30]	7.633	5.783
	Subjective Life satisfaction	The substitute variable of the robustness test, whether satisfied with life: 1 = satisfied, 0 = dissatisfied	0.926	0.262
Independent Variable	Living arrangements	1 = living alone or living with a spouse only, 0 = living with children	0.419	0.493
Moderating variable	Internet use	Whether older adults use the Internet: 1 = yes, 0 = no	0.073	0.261
	Available Internet connections	Whether there is an Internet connection at home: 1 = Yes, 0 = No	0.073	0.261
	Frequency of Internet use	Frequency of Internet use in the last month: [1,4], never, occasionally, almost every week, almost daily	1.205	0.744
	Chatting	Whether you can use the Internet for chatting: 1 = yes, 0 = no	0.044	0.205
	Entertainment	Whether you can use the Internet for entertainment: 1 = yes, 0 = no	0.055	0.227
	Information acquisition	Whether you can use the Internet to get information: 1 = yes, 0 = no	0.061	0.239
	Financial management	Whether you can use the Internet for financial management: 1 = yes, 0 = no	0.005	0.07
Personal characteristics	Age	Actual age	68.799	6.363
	Sex	Sex of older adults: 1 = male, 0 = female	0.482	0.5
	Marital status	Whether has a spouse living together: 1 = yes, 0 = no	0.894	0.308
	Physical health	Whether older adults are healthy: 1 = healthy, 0 = unhealthy	0.218	0.413
Social structural characteristics	Education level	The educational level of older adults: [1,4], illiterate, elementary school and below (literate), middle school, high school, and above	2.075	0.966
	Total income	Total number of income in a year (yuan)	10914.685	20376.547
	Place of residence	Place of residence: 1 = urban, 0 = rural	0.271	0.445

2. Model 4 replaces Internet use by using available Internet connections, frequency of Internet use, and patterns of Internet use and examines the specific impact of Internet use from three dimensions.

Table 2 shows that living arrangements have a significant impact on the mental health status of older adults (Model 1 and Model 2). Under the condition of controlling personal characteristic variables and regional characteristic variables, the estimation results show that the level of depression index for older adults who live not with children is significantly higher than that for older adults who live with children ($p < 0.01$). At the same time, it can be seen that personal information variables and regional affiliation variables have a significant impact on mental health status. The level of depression is significantly higher among older adults who are male, single, unhealthy, poorly educated, with low income, and living in rural areas. Hypothesis 1 is verified.

Model 3 shows that Internet use significantly reduces the depression index of older adults. Compared with older adults who do not use the internet, older adults who use the Internet do have a lower level of depression index ($p < 0.01$). Hypothesis 2 is verified.

Model 4 indicates that the three dimensions of Internet use have different effects on the mental health of older adults. Available Internet connections and frequency of Internet use both do not have a significant impact on the mental health of older adults ($p > 0.1$). Hypothesis 2.1 and Hypothesis 2.2 are rejected. From the regression coefficient, available Internet connections can reduce the level of depression in older adults, but the higher the frequency of Internet use, the higher the level of depression in older adults. In addition, different Internet use patterns also have different effects on the mental health of older adults. Using the information acquisition function can significantly reduce depression levels in older adults ($p < 0.1$). However older adults who use the financial management function are more depressed than those who do not use this function ($p < 0.05$). The other two patterns of Internet use (chatting and entertainment) have no significant effect on the mental health of older adults ($p > 0.1$). Hypothesis 2.3 is partly verified and partly rejected, indicating the intricate nature of the mechanisms associated with Internet use.

3.2 Robustness test

3.2.1 PSM

As the living arrangements of older adults are a self-selecting behavior, there are significant differences between the group living

TABLE 2 Results of OLS regression analysis for living arrangements, internet use, and mental health of older adults.

	Model 1	Model 2	Model 3	Model 4
Living arrangements	0.340***	0.445***	0.453***	0.455***
	(0.089)	(0.085)	(0.085)	(0.085)
Internet use			−0.888***	
			(0.174)	
Available Internet connections				−1.126
				(0.868)
Frequency of Internet use				0.283
				(0.284)
Chatting				−0.210
				(0.315)
Entertainment				0.200
				(0.355)
Information acquisition				−0.799*
				(0.411)
Financial management				1.369**
				(0.607)
Control variable	No	Yes	Yes	Yes
Constant	7.490***	10.296**	10.626**	10.357**
	(0.058)	(4.192)	(4.189)	(4.196)
N	17,243	17,243	17,243	17,243
Adj. R^2	0.0008	0.1278	0.1290	0.1293

(1) Standard errors in parentheses. (2) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

TABLE 3 Results of propensity score matching estimation of living arrangements on the mental health of older adults.

	Treated	Controls	ATT	S.E.	T-stat
Kernel	7.833	7.412	0.421	0.093	4.51***
Neighbor (4)	7.833	7.519	0.314	0.111	2.83***
Radius	7.833	7.410	0.423	0.093	4.54***
Llr	7.833	7.481	0.353	0.124	2.84***

independently (treatment group) and the group living with children (control group) in many aspects, such as age, sex, marital status, education level, and urban–rural differences. Although the OLS model controls these confounding variables, it is difficult to solve the self-selection problems effectively. Therefore, the PSM method is introduced to further validate the robustness of the model.

Table 3 shows the average treatment effect on the treated (ATT) of living arrangements on the mental health of older adults. The results show that the average treatment effects obtained through these four matching methods are significant at the 1% level. The matching outcomes indicate that, after eliminating sample biases between the control and the treatment groups, living arrangements still have a significant impact on the mental health of older adults. Additionally, it can be observed that the average treatment effect on the treated (ATT) derived from neighbor (4) matching, radius matching, and kernel matching are relatively close, which corroborates the robustness of the previous research findings and further confirms Hypothesis 1. Figure 1 shows the changes in kernel density plots before and after matching. From the distribution of nuclear density of PSM score in different groups, it can be seen that the difference between the treatment group and the control group was smaller after matching compared to before matching. In general, after controlling for the influence of confounding variables in the sample, living arrangements still have a genuine and significant effect on the mental health of older adults.

3.2.2 Substituting dependent variable

This paper used a replacement model and a replacement variable to verify such research results. We replaced the dependent variable with life satisfaction and treated it as a binary "dummy" variable that was assigned a value of 0 for dissatisfaction and a value of 1 for satisfaction. Then, logit regression was used to test the effect of living arrangements and Internet use on life satisfaction (Model 5, Model 6, and Model 7).

Table 4 shows that the effects of both living arrangements (Model 5) and Internet use (Model 6 and Model 7) on life satisfaction were

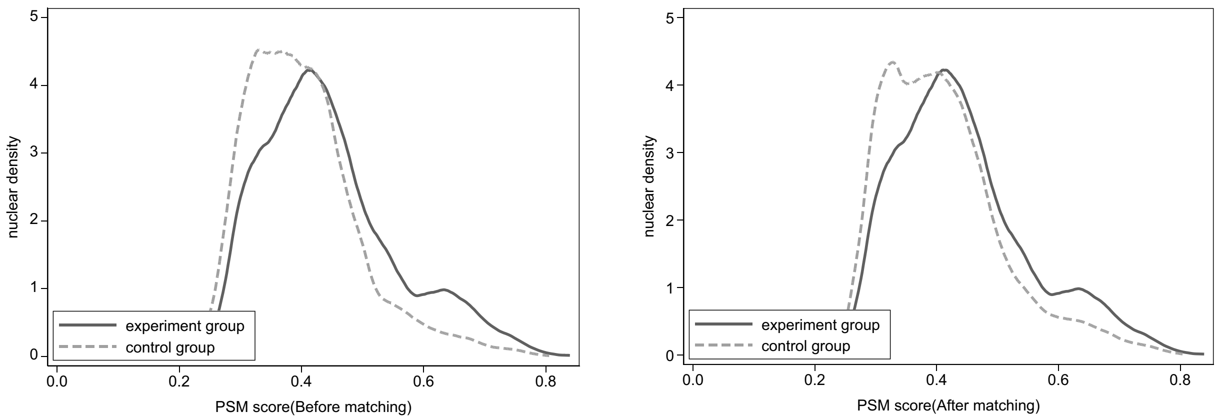

FIGURE 1
Changes in nuclear density before and after matching.

TABLE 4 Robustness tests of the influence of living arrangements on the mental health of older adults and the moderating effect of Internet use.

	Model 5	Model 6	Model 7
Living arrangements	−0.140**	−0.141**	−0.142**
	(0.06129)	(0.061)	(0.061)
Internet		0.488**	
		(0.214)	
Available Internet connections			2.044
			(1.483)
Frequency of Internet use			−0.551
			(0.496)
Chatting			−0.179
			(0.442)
Entertainment			−0.374
			(0.504)
Information acquisition			0.728
			(0.466)
Financial management			−1.616***
			(0.580)
Control variable	Yes	Yes	Yes
Constant	3.929	3.697	4.164
	(2.873)	(2.872)	(2.909)
N	17,243	17,243	17,243
Pseudo R^2	0.0592	0.0600	0.0610

(1) Standard errors in parentheses; (2) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

statistically significant, which is consistent with the baseline regression results. This supports our conclusion that older adults living independently have significantly lower levels of mental health than those who do not, and Internet use can significantly improve the mental health of older adults. The three dimensions of Internet use also have different effects on the life satisfaction of older adults, and only the use of the financial management function has a significant negative effect on life satisfaction.

3.3 Heterogeneity analysis

In the previous study, it was found that older adults who were male, single, unhealthy, poorly educated, with low income, and living in rural areas obtained a significantly higher depression index score. As education level, total income, and place of residence reflect the social structural differences, we chose these three variables to carry out the heterogeneity analysis (Tables 5, 6). It can be seen that the

TABLE 5 Influence of living arrangements on the mental health of older adults with different levels of education.

	Model 8	Model 9	Model 10	Model 11
	Illiterate	Elementary school and below (literate)	Middle school	High school and above
Living arrangements	0.547***	0.320**	0.440**	0.707***
	(0.171)	(0.135)	(0.179)	(0.214)
Available Internet connections	1.863	−0.791	−1.210	−0.572
	(4.163)	(1.761)	(1.497)	(1.168)
Frequency of Internet use	0.597	0.415	0.038	0.253
	(1.633)	(0.575)	(0.480)	(0.375)
Chatting	−5.478*	−0.481	1.255**	−0.620
	(2.893)	(0.702)	(0.498)	(0.404)
Entertainment	−1.832	0.884	−0.222	0.276
	(3.173)	(0.757)	(0.548)	(0.473)
Information acquisition	0.699	−2.250***	−0.736	−0.985
	(2.834)	(0.774)	(0.687)	(0.619)
Financial management		0.577	0.849	1.548**
		(2.272)	(1.002)	(0.668)
Control variable	Yes	Yes	Yes	Yes
Constant	−5.091	16.272**	26.205***	31.224***
	(7.834)	(7.112)	(9.972)	(10.450)
p value	0.000***			
N	5,527	6,810	2,989	1,917
R^2	0.074	0.099	0.105	0.135

(1) Standard errors in parentheses; (2) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

heterogeneity analyses of each group passed the Chow test, indicating that the differences between the groups were significant.

Table 5 shows the relationship between living arrangements, Internet use, and mental health of older adults with different levels of education, and it can be seen that there were significant differences between the four groups (Chow test: p-value<0.001). For all four groups, older adults who do not live with their children had significantly higher levels of depression than those who live with their children. However, different dimensions of Internet use had different effects on the mental health of older adults with different levels of education. For the illiterate group, chatting significantly reduced the level of depression in older adults. However, for the middle school group, chatting significantly increased the level of depression in older adults. For the other two groups (elementary school and below (literate), high school, and above), chatting had no significant effect on the level of depression in older adults. Except for the illiterate group, information acquisition significantly reduced the level of depression in older adults in the other three groups, especially for the elementary school and below (literate) group ($p < 0.01$). Meanwhile, financial management increased the level of depression in older adults, especially in the high school and above group ($p < 0.05$).

Table 6 shows the relationship between living arrangements, Internet use, and mental health of older adults in the low-income and high-income groups and in urban and rural areas. The results showed that there was a significant difference between the low-income group and the high-income group (Chow test: p-value<0.05). The living arrangements of older adults in the low-income group had a significant impact on their mental health. The depression level of older adults who do not live with their children was significantly higher than that of older adults who live with their children. However, the living arrangements of older adults in the high-income group had no significant effect on their mental health. In terms of Internet use, information acquisition and financial management had a significant impact on the mental health of older adults in the low-income group. Information acquisition significantly reduced the depression level of older adults in the low-income group, but financial management significantly increased the depression level of older adults in the low-income group. For older adults in the high-income group, all dimensions of Internet use had no significant impact on their mental health.

The difference between urban and rural groups was equally significant (Chow test p-value<0.001). Regardless of urban and rural areas, the living arrangements of older adults had a significant impact on their mental health, and living with their children significantly reduced the level of depression in older adults. However, the impact of Internet use differed between the two groups. For rural older adults, information acquisition significantly reduced their depression levels ($p < 0.01$), while for urban older adults, information acquisition had no significant effect on their depression levels. For urban older adults, financial management significantly increased their depression levels, while for rural older adults, financial management had no significant impact on their depression levels. According to the regression

TABLE 6 Influence of living arrangements on the mental health of older adults with different levels of income and place of residence.

	Model 12	Model 13	Model 14	Model 15
	Low income	High income	Rural	Urban
Living arrangements	0.452***	0.400	0.409***	0.544***
	(0.091)	(0.243)	(0.102)	(0.153)
Available Internet connections	−1.259	−1.054	0.043	−1.700
	(0.945)	(2.330)	(1.352)	(1.087)
Frequency of Internet use	0.339	−0.402	0.145	0.258
	(0.310)	(0.753)	(0.446)	(0.354)
Chatting	−0.221	0.527	0.224	−0.214
	(0.328)	(1.233)	(0.619)	(0.347)
Entertainment	0.005	2.323	−0.012	0.499
	(0.369)	(1.488)	(0.673)	(0.394)
Information acquisition	−0.950**	−1.261	−2.403***	−0.100
	(0.431)	(1.568)	(0.720)	(0.474)
Financial management	1.070*	0.922	−0.617	1.362**
	(0.615)	(3.954)	(1.889)	(0.601)
Control variable	Yes	Yes	Yes	Yes
Constant	5.627	23.660**	6.223	18.034**
	(4.777)	(10.848)	(5.158)	(7.119)
P-value	0.0131**		0.000***	
N	14,910	2,333	12,566	4,677
R^2	0.129	0.108	0.108	0.133

(1) Standard errors in parentheses; (2) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

coefficient, financial management also reduced the level of depression of rural older adults.

3.4 Moderating effect test

Table 7 verifies the moderating mechanisms of Internet use in the influence of living arrangements on the mental health of older adults (Model 16) and the specific moderating mechanisms of the three main dimensions of Internet use (Model 17). Model 16 shows that living arrangements significantly affect the mental health of older adults. Compared to older adults who live with their children, those who do not live with their children have significantly higher levels of depression. Internet use had a significant impact on the mental health of older adults, and it significantly reduced the level of depression among older adults. However, the Living*Internet interaction term did not pass the significance test, indicating that Internet use did not play a moderating role. According to the regression coefficient, Internet use weakened the influence of living arrangements on the mental health of older adults.

Model 17 further verifies which elements of Internet use play a moderating role in the process of living arrangements affecting the mental health of older adults and how they play a moderating role. It was found that available Internet connections and frequency of Internet use did not play a significant moderating role in the process of living arrangements affecting the mental health of older adults. In terms of the coefficient of the interaction term, available Internet connections weakened the effect of living arrangements, while the frequency of Internet use strengthened the effect of living arrangements. Meanwhile, according to Model 17, it was found that all patterns of Internet use significantly moderated the effect of living arrangements on the mental health of older adults. Among them, chatting and information acquisition significantly weakened the effect of living arrangements ($p < 0.1$), indicating that chatting and information acquisition through the Internet reduced the level of depression among older adults who do not live with their children. However, entertainment and financial management significantly enhanced the effect of living arrangements ($p < 0.05$), suggesting that entertainment and financial management through the Internet strengthened the level of depression among older adults who do not live with their children. This may be because chatting and information acquisition through the Internet can strengthen bidirectional and multidimensional communication between older adults and the outside world, while entertainment and financial management through the Internet are more likely to substitute for the social needs of older adults in the real world and enhance unidirectional communication toward the virtual world. Model 17 partially verifies Hypothesis 3, which supports the existence of a moderating effect of Internet use. However, Model 17 also demonstrates the complexity of the moderating mechanism, with inconsistent directions of moderation. Specifically, some patterns of Internet use have an enhancing effect, while others have a weakening effect, and there are two dimensions (available Internet connections and frequency of Internet use) that do not exhibit any moderating effect.

TABLE 7 Test of the moderating mechanism of Internet use for the influence of living arrangements on the mental health of older adults.

	Model 16	Model 17
Living arrangement	0.454***	0.535***
	(0.088)	(0.147)
Internet use	−0.859***	
	(0.219)	
Living*Internet	−0.143	
	(0.315)	
Available Internet connections		−0.986
		(1.139)
Frequency of Internet use		0.193
		(0.372)
Chatting		0.175
		(0.413)
Entertainment		−0.605
		(0.484)
Information acquisition		−0.021
		(0.507)
Financial management		−0.549
		(0.915)
Living*Available Internet connections		−0.698
		(1.732)
Living*Frequency of Internet use		0.393
		(0.571)
Living*Chatting		−1.064*
		(0.630)
Living*Entertainment		1.648**
		(0.707)
Living*Information acquisition		−1.557*
		(0.873)
Living*Financial management		3.126**
		(1.214)
Control variable	Yes	Yes
Constant	11.106***	10.918***
	(4.092)	(4.106)
N	17,457	17,457
Adj. R^2	0.1289	0.1296

(1) Standard errors in parentheses; (2) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4 Discussion

The following revelations can be drawn from the results of the experiment.

The living arrangements of older adults have a significant impact on their mental health. Compared to older adults who live with their children, those who do not live with their children have significantly higher levels of depression, which is consistent with results of previous studies (10). As older adults are more dependent on social support, living alone may lead to insufficient interaction between older adults and their family and friends, which can lead to a greater risk of depression (31). Moreover, living alone can also increase the risk of poverty among older adults (32), thus increasing the psychological stress of older adults. At the same time, as the family remains the main source of support for older adults in China (33), Living with children can not only promote communication between older adults and their children (34) but also give older adults a sense of pride in Chinese cultural while helping older adults to obtain instrumental and emotional support from their children (35), thus maintaining the mental health of older adults.

Internet use has a significant effect on the mental health of older adults. Similar to previous studies, we confirmed that Internet use can significantly promote mental health for older adults (21, 24). This is because the Internet can provide with older adults all kinds of information, various forms of entertainment opportunities, and convenient and fast social interactions (36). Internet use not only helps older adults interact with their family but also helps them keep up with current events and access entertainment (37). Above all, the social functions of the Internet have the most obvious positive effect on mental health. Older adults can promote their mental health by communicating with family and friends through email (38) and online chat.

There are significant differences in the relationship between living arrangements, Internet use, and the mental health of older adults across different groups (education level, income, and urban and rural areas). In particular, the degree and direction of the impact of Internet use vary among different groups. Internet use plays a moderating role in the impact of living arrangements on the mental health of older adults, but it is necessary to look specifically at the moderating mechanisms for different dimensions of Internet use. In general, the social attributes of the Internet (chatting and information acquisition) can weaken the impact of living arrangements on the mental health of older adults, while unidirectional Internet use (entertainment and financial management) strengthens the impact of living arrangements on the mental health of older adults. At the same time, whether older adults are connected to the Internet and the frequency of Internet use does not have a moderating effect in the impact of living arrangements on the mental health of older adults. The reason is that Internet use can enhance communication between older adults and their children (39) and help older adults maintain a close intergenerational relationship (40). At the same time, Internet use also helps older adults meet new friends (41) and expand their social network, thus maintaining close contact with society (42).

The study still has some limitations. First, as the data used in this study were collected in 2018, this study does not reflect the situation at present. Second, although we have used five control variables (age, sex, education level, physical health, and place of residence), it is still difficult to rule out possible conflations caused by factors such as socioeconomic level. Furthermore, this study revealed the complex mechanisms by which Internet use moderates the impact of living arrangements on the mental health of older adults. The measurement of Internet use was multidimensional, and its moderating mechanisms exhibited both compensatory and substitutive effects. This paper only investigated Internet use as a moderating variable and did not explore how Internet use affects the mental health of older adults and its underlying mechanisms. However, based on the existing findings, we believe that it is necessary to conduct dedicated research on the mechanisms by which Internet use influences the mental health of older adults, including whether these mechanisms change with changes in variables such as age. This will be the direction for future research.

5 Conclusion

This paper concludes that older adults living with their children have better mental health than those living independently. In addition, Internet use is beneficial in promoting mental health among older adults and the relationship between living arrangements, Internet use, and mental health is evident. Finally, this study supports the moderating effect of Internet use, which has policy implications for improving the mental health of older adults in the digital age. However, the mechanism of the role of the Internet should be analyzed specifically and cannot be discussed in general terms.

Living arrangements reflect intergenerational support to a certain extent, and living with children can significantly reduce the level of depression of older adults. This indicates that the spiritual comfort function of family care is still very prominent. Even in the digital age, family care for older adults is still very important. Therefore, the government can encourage older adults to live with their children in order to improve their mental health. If it is really impossible to live together, the government should encourage the children of older adults to use the Internet to strengthen their care for older adults and provide them with the necessary emotional support.

At the same time, the government can integrate the strength of families and peer groups to provide targeted digital education for older adults, guide them to screen Internet content effectively, help them develop good habits of Internet use, enhance their ability to use the Internet, so as to help older adults to enjoy the benefits of Internet use as much as possible.

On the one hand, it is necessary to reasonably guide older adults to use the Internet to expand their social communication (chatting and obtaining information). Utilizing the Internet to expand the connections between older adults and the real-world society is feasible because Internet use transcends spatial constraints and enables children who do not live with their parents to provide support through the Internet. This can partly diminish the need for older adults to rely on face-to-face support from their children. On the other hand, it is important to be aware of the potential risks associated with Internet use. While the Internet can provide necessary support for older adults, it may also expose them to the risk of becoming immersed in the virtual world through activities such as watching videos, playing online games, and financial management online. Consequently, this may lead to the impairment of their mental health.

Therefore, the government and social service departments must assist older adults in establishing correct concepts of Internet use, enhancing their digital literacy, and improving their digital skills.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

This study was based on publicly available datasets. Ethical review and approval was not required for the study, in accordance with the local legislation and institutional requirements.

Author contributions

RZ: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. WN: Conceptualization, Methodology, Software, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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